

Optimization of a pulse generator for the evaluation of CTA FlashCam readout electronics and development of a calibration chamber for detector testing.

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Matthias Biegger

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Optimization of a pulse generator for the evaluation of CTA FlashCam readout electronics and development of a calibration chamber for detector testing.

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Abstract

The first part of this thesis deals with the optimization of a pulse generator for the evaluation of CTA FlashCam readout electronics. FlashCam is a camera for the Medium-Sized Telescopes of the upcoming CTA observatory based on photomultiplier tubes. The handling, functionality as well as the output properties of the output signals of a pulse generator were revised. The pulse generator, managed by an FPGA, can be operated either in an internal or an external trigger mode, controlling eight output signals with individual signal properties. The requested signal of the pulse generator is a sharp gradient with an adjustable voltage difference. The rise time of this sharp gradient was measured to be about $t_{\text{rise}} = 2.1 \text{ ns}$.

The second part of this thesis concentrates on the construction of a calibration chamber (darkbox setup) for detector operation. A light tightness measurement using photomultiplier tubes showed a remaining trigger rate of about 5 events/s and therefore, the darkbox is opaque for optical light. The measured trigger rate might be caused of dark counts instead of optical photons. Inside the darkbox setup there are a laser with 405 nm wavelength, a filter wheel and a diffuser for detector exposure. The resulting light cone is homogeneous for detectors with an effective area of about 150 mm^2 .

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Chapter 1

Introduction

The observation of the cosmos enables astronomers to study galactic and extragalactic sources. To get as much information as possible, a source should be observed in different energy bands of the electromagnetic spectrum. Depending on the physical processes of a source, only a small interval of photon energy could be emitted (see for example Córdova (1988) for further information). By observing in different energy bands of the electromagnetic spectrum, sources and phenomena can be investigated that are unseen in other energy bands. To cover all available photon energies, it is necessary to develop telescopes specialized in the observation of the respective energy range, because depending on its energy a photon has varying scattering and absorption properties. For an introduction to astronomy at different energies and their techniques, see for example Léna et al. (2012) or Kitchin (2013).

1.1 Gamma-ray astronomy

The most energetic band of the electromagnetic spectrum is the gamma-ray band. The transition energy of the X-ray and the gamma-ray spectrum is not defined consistently in literature, but is of the order of hundreds of keV. Sources emitting photons with such energies are for example supernova remnants, X-ray binaries, pulsar wind nebulae, active galactic nuclei, galaxy clusters or gamma-ray bursts (Cheng and Romero, 2012). In gamma-ray astronomy, astronomers observe either by using ground-based or space-based telescopes, depending on the photon flux and the photon energy of the respective energy range. The topic of this thesis is related in the field of ground-based gamma-ray astronomy.

High energy photons of the gamma-ray spectrum interact with the atmosphere of the Earth creating an electromagnetic shower. The initial photon interacting with an atmospheric molecule (or particle) creates an

electron-positron pair with a rest mass of $511 \text{ keV}/c^2$ per particle (Ross-wog and Brüggem, 2007). The created particles can emit further photons because of bremsstrahlung (Rybicki and Lightman, 1979). This sequence is repeated as long as the photons have enough energy for the electron-positron pair production. According to Gaisser et al. (2016), this energy is calculated to be $E \approx 87 \text{ MeV}$. Below this energy threshold, scattering or absorption processes are dominating. In a simple model (see Figure 1.1),

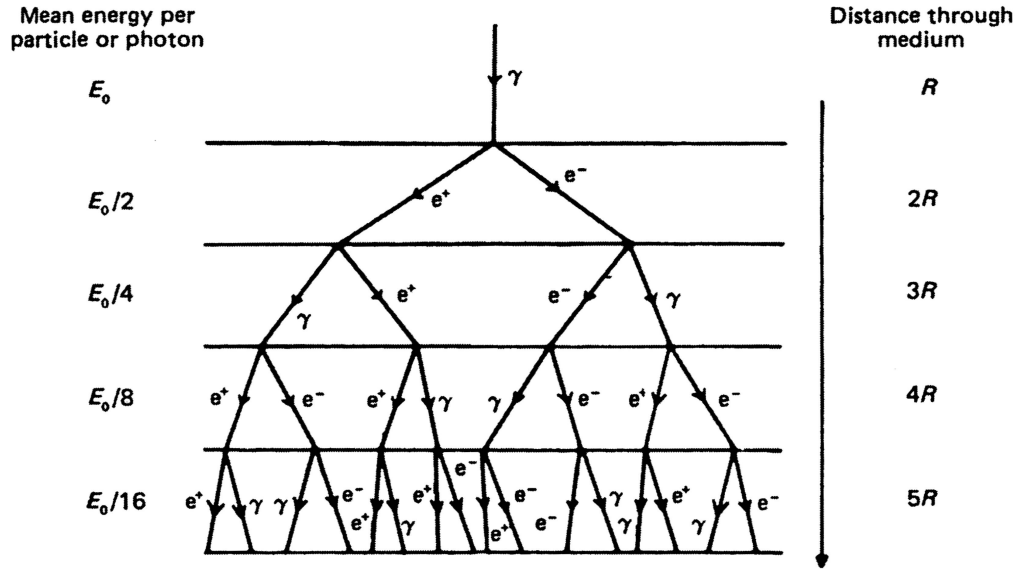


Figure 1.1: A simple model for an electromagnetic shower. The initial photon creates an electron-positron pair. Those particles emit further photons. This sequence continues until there is not enough energy left for a single photon to undergo pair production. Image: Longair (2012).

it is assumed that after a distance R a particle or photon shares its energy equally to the following two particles or photons. Assuming an initial photon energy of 10 TeV ,

$$N = \frac{10 \text{ TeV}}{87 \text{ MeV}} \sim 10^5 \quad (1.1)$$

particles and photons with an energy of 87 MeV each are created.

Another possibility to create particle showers are charged cosmic rays¹ as initial particles (see Figure 1.2). Those particle showers are a source of background and need to be discriminated from the particle showers caused by photons. A cosmic ray interacting with the atmosphere can create pions

¹Cosmic rays are composed of $\sim 99\%$ nuclei like protons or helium and of $\sim 1\%$ electrons with an energy of up to $\sim 1 \times 10^{20} \text{ eV}$.

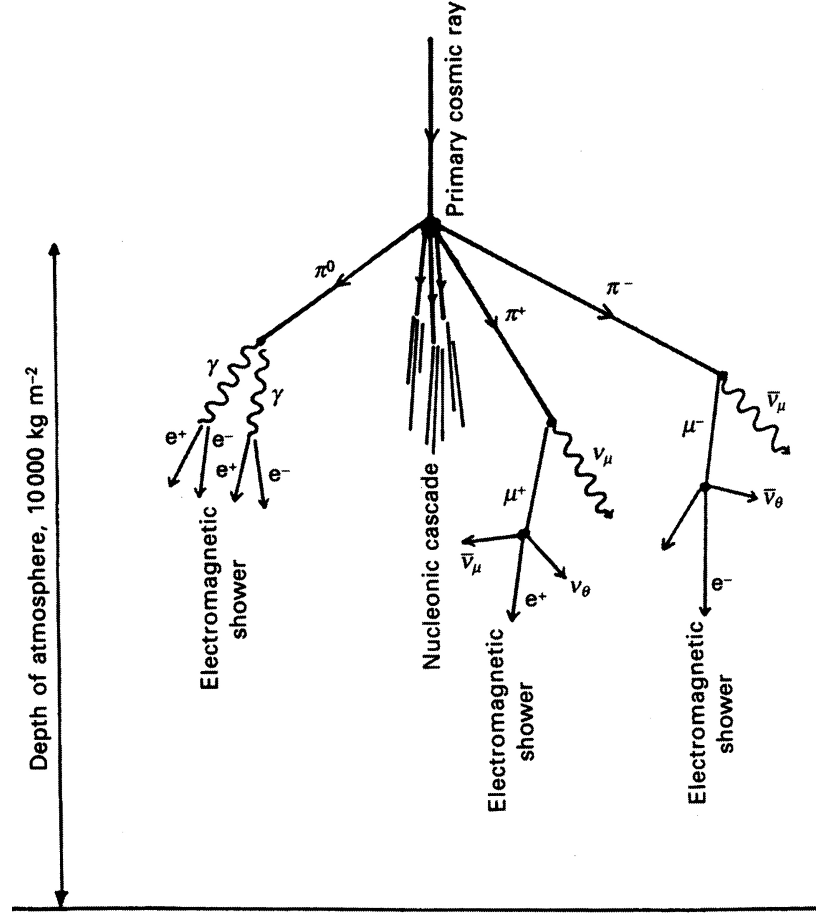


Figure 1.2: A diagram showing a hadronic shower model. The primary cosmic ray creates a nucleonic cascade. Beside this nucleonic cascade, pions are created initializing electromagnetic showers (see Figure 1.1). Image: Longair (2012).

(π^0 , π^- or π^+). Depending on their compositions, the pions decay and cause different subshowers. The following information of the particle decays were taken from Beringer et al. (2012).

- π^0 : This neutral charged particle with a half life period of about 8.5×10^{-17} s decays with a probability of $\sim 99\%$ into two photons or with a probability of $\sim 1\%$ into electron, positron and photon. With both scenarios the π^0 creates in the end an electromagnetic shower.
- π^- : The π^- with a half life period of about 2.6×10^{-8} s decays with a probability of almost 100% into a muon and an anti muon neutrino. The muon furthermore decays with a half life period of about 2.2×10^{-6} s into an electron, a muon neutrino and an anti

electron neutrino. After those decays, there is an electromagnetic shower as well².

- π^+ : Since the positive charged pion is the anti particle of the negative charged pion, it creates the antiparticles of the case before also resulting in an electromagnetic shower.

The particle showers are observed by measuring Cherenkov radiation emitted by the electromagnetic showers (see Subsection 1.1.1). The Cherenkov radiation is measured with Cherenkov telescopes which are explained in Subsection 1.1.2. The hadronic showers caused by cosmic rays are background for those measurements and need to be identified to distinguish between signal and background.

1.1.1 Cherenkov radiation

According to Grupen (2005), a charged particle passing through a dielectric medium induces polarization (of this medium). Cherenkov radiation is emitted, if the particle has a velocity v greater than the speed of light in the medium

$$v > c/n \quad , \quad (1.2)$$

where c is the speed of light in vacuum and n is the refraction index of the medium. The energy of the emitted radiation is of the order of some electronvolts and therewith it is located in the visible and ultra violet band of the electromagnetic spectrum.

The wavefront of the emitted radiation can be constructed by drawing circles for different positions of the charged particle in the medium (see Figure 1.3). The angle θ of the wavefront can be calculated and depends on the velocity of the particle and the refraction index of the medium. For dry air and standard atmospheric conditions ($T_{\text{atm}} = 15^\circ\text{C}$ and $P_{\text{atm}} = 1013.25 \text{ mbar}$), the refraction index is according to Haynes (2012)

$$n_{\text{air}} = 1.00028 \quad . \quad (1.3)$$

With the speed of light in vacuum of $c = 2.9979 \times 10^{10} \text{ cm/s}$ (Rosswog and Brüggen, 2007) and Equation (1.3), the threshold velocity for electrons emitting Cherenkov radiation can be calculated

$$v_{\text{th}} = \frac{c}{n_{\text{air}}} = 0.99972c = 2.9971 \times 10^{10} \text{ cm/s} \quad (1.4)$$

²Note that a large fraction of muons reach the surface of the Earth before decaying due to time dilatation.

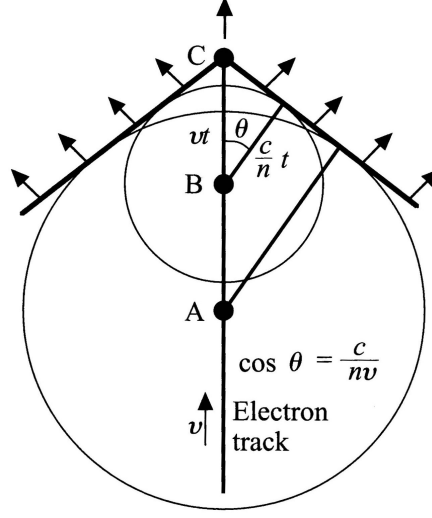


Figure 1.3: Construction of the wavefront of Cherenkov radiation for an electron with the velocity v passing through a medium with the refraction index n . Image: Bradt (2004).

which is equal to a relativistic energy of the electron of

$$E_{\text{th}} = \gamma m_0 c^2 = \frac{m_0 c^2}{\sqrt{1 - \left(\frac{v_{\text{th}}}{c}\right)^2}} = 21.6 \text{ MeV} \quad (1.5)$$

with the rest mass energy of an electron $E_0 = m_0 c^2 = 511 \text{ keV}$ (Rosswog and Brüggen, 2007) and the Lorentz factor γ . To detect the Cherenkov radiation emitted by electrons with an energy above the calculated threshold E_{th} and therewith to trace back the origin of the initial photon and estimate its energy is the idea of Cherenkov telescopes for gamma-ray astronomy which are introduced in Subsection 1.1.2.

1.1.2 Imaging Atmospheric Cherenkov Telescopes

Cherenkov telescopes are built to detect the Cherenkov radiation (see Subsection 1.1.1) coming from electromagnetic showers which were created in the atmosphere of the Earth. Since there are typically low fluxes in the gamma-ray band³, the benefit of Cherenkov telescopes is the collecting area for incoming gamma-rays which is much larger than their mirror size, as it is shown in Figure 1.4. This large collecting area can compensate

³The Crab nebula (supernova remnant and pulsar wind nebula) is a bright gamma-ray source with a flux of $F_{E>200 \text{ GeV}} = (1.96 \pm 0.05) \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$ (Albert et al., 2008).

the low gamma-ray fluxes. Cherenkov telescopes are operated usually as telescope array to realize a higher sensitivity (larger effective area and a better signal to noise ratio) as well as to achieve a better accuracy in the reconstruction of the direction and energy of the initial photon.

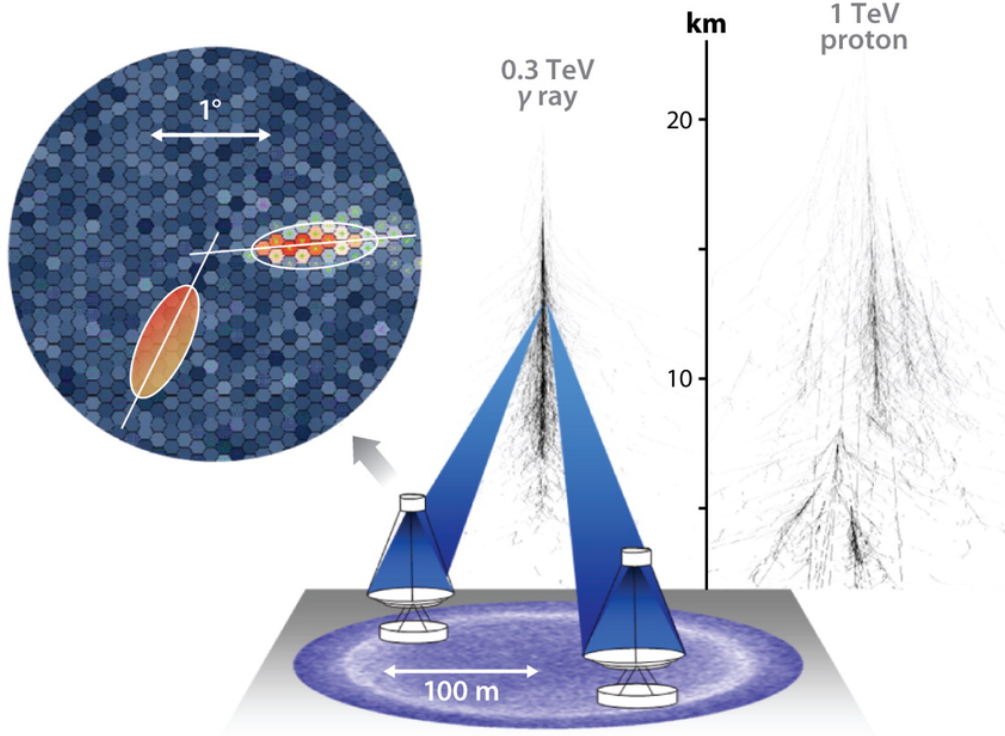


Figure 1.4: Detection of Cherenkov radiation emitted by an electromagnetic shower. The light projected on the ground is shown as well as the signals of the Cherenkov radiation on the cameras of the Cherenkov telescopes. By operating the telescopes as an telescope array, the sensitivity and the reconstruction of the properties of the initial photon is improved. A hadronic shower would cause a more scattered image on the telescopes. Image: Hinton and Hofmann (2009).

Since Cherenkov telescopes need to detect low fluxes of photons with energies of some electronvolts, they comprise large mirror areas to reflect the photons to the detection plane. The detector itself should have a high photon detection efficiency and a good time resolution, because the duration of the electromagnetic shower is only several nanoseconds (Aharonian et al., 2013). These requirements are fulfilled by photomultiplier tubes, consisting of a photocathode, a focusing electrode, several dynodes and an anode (see Figure 1.5).

According to Shore (2003), a photon with an energy of some electron-

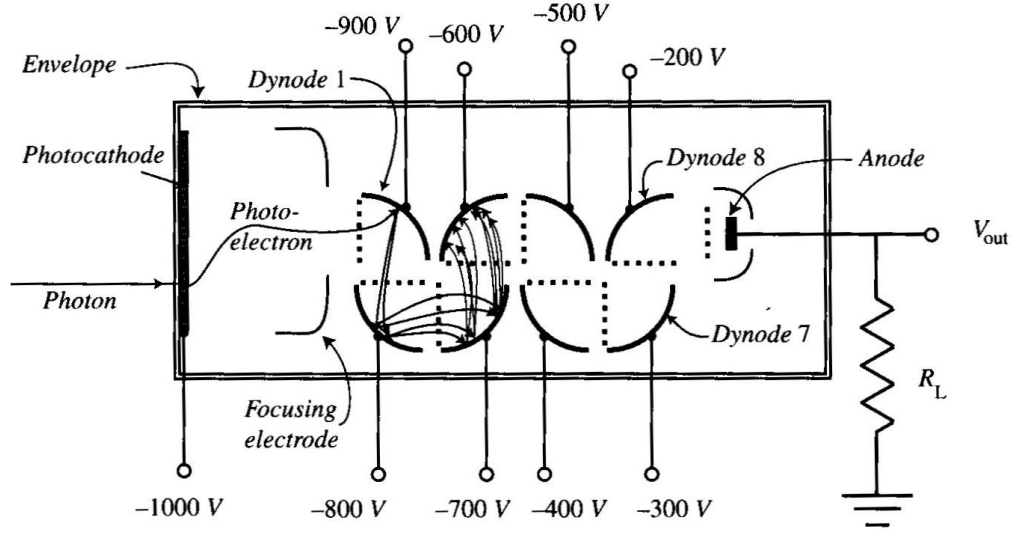


Figure 1.5: Constitution of a photomultiplier tube. Beginning from the left side, there is a photocathode, a focusing electrode, several dynodes at different potentials and an anode. Image: Chromey (2010).

volts is able to unbound an electron from the photocathode. This electron gets focussed by the focusing electrode and accelerated by the high voltage applied to the dynodes. Whenever an accelerated energetic electron hits a dynode, secondary electrons are emitted. Depending on the applied high voltage, one visible photon is able to cause a number of electrons which is a detectable amount of charge.

There are currently (year 2017) three major IACT (**I**maging **A**tmospheric **C**herenkov **T**elescope) observatories in operation: *H.E.S.S.* (**H**igh **E**nergy **S**tereoscopic **S**ystem, see for example Schüssler (2017) for further information), *MAGIC* (**M**ajor **A**tmospheric **G**amma **I**maging **C**herenkov Telescopes, see for example Aleksić et al. (2016) for further information) and *VERITAS* (**V**ery **E**nergetic **R**adiation **I**maging **T**elescope **A**rray **S**ystem, see for example Holder (2017) for further information). Those observatories are composed of 2...5 telescopes each with diameters between 12 m...28 m (see Table 1.1). According to Bigongiari (2016), more than 170 sources have been detected using IACTs. The new generation of IACT array is already in design: The Cherenkov Telescope Array, which is presented in Section 1.2.

Table 1.1: Currently (year 2017) operating Imaging Atmospheric Cherenkov Telescopes are listed with their location and altitude of the observatories asl (**a**bove **s**ea **l**evel), the number of telescopes, the diameter of the mirrors, the field of view, the threshold energy and the sensitivity according to Falkenburg and Rhode (2012) and Hinton (2009).

Name	H.E.S.S.	MAGIC	VERITAS
Location	Namibia	La Palma	Arizona
Altitude in m	1800	2225	1270
Number of telescopes	4 + 1	2	4
Diameter in m	12 and 28	17	12
Field of view in $^{\circ}$	5	3.5	3.5
Threshold energy in TeV	0.1	0.06	0.1
Sensitivity in % Crab	0.7	2	1

1.2 Cherenkov Telescope Array - CTA

The CTA (**C**herenkov **T**elescope **A**rray) is a new IACT observatory planned by about 1350 scientists and engineers in 210 institutions from 32 countries. According to Acharya et al. (2013), CTA is expected to detect more than 1000 sources. There will be two locations to cover the whole sky. The CTA consortium decided for the Northern Hemisphere the island of La Palma and for the Southern Hemisphere the Atacama Desert in Chile to be the two CTA sites. CTA will be composed of three different telescope sizes, the SST (**S**mall-**S**ized **T**elescope), MST (**M**edium-**S**ized **T**elescope) and LST (**L**arge-**S**ized **T**elescope) with diameters of 4 m, 12 m and 23 m. While the LST is designed to reconstruct photons with energies down to a few tens of GeV, the SST is designed to cover a large area of the atmosphere of the Earth and therewith to increase the sensitivity of CTA for the upper energy limit. Covering a large area of the atmosphere of the Earth could also be achieved by using many LSTs, but it is more cost efficient using MSTs and SSTs for the highest energies. Figure 1.6 shows the sensitivity of CTA color coded for the three telescope types.

Figure 1.7 shows an artist's view of a possible configuration of CTA telescopes. The LSTs are placed close together and represent the center of the telescope array surrounded by the MSTs. The SSTs are placed at larger distances to realize the coverage of a large area.

According to Actis et al. (2011), with this configuration CTA is expected to have a sensitivity of a factor of 10 better compared to current IACT experiments (see Table 1.1). The energy range of CTA is located between some tens of GeV to beyond 100 TeV and therewith it will cover up to four

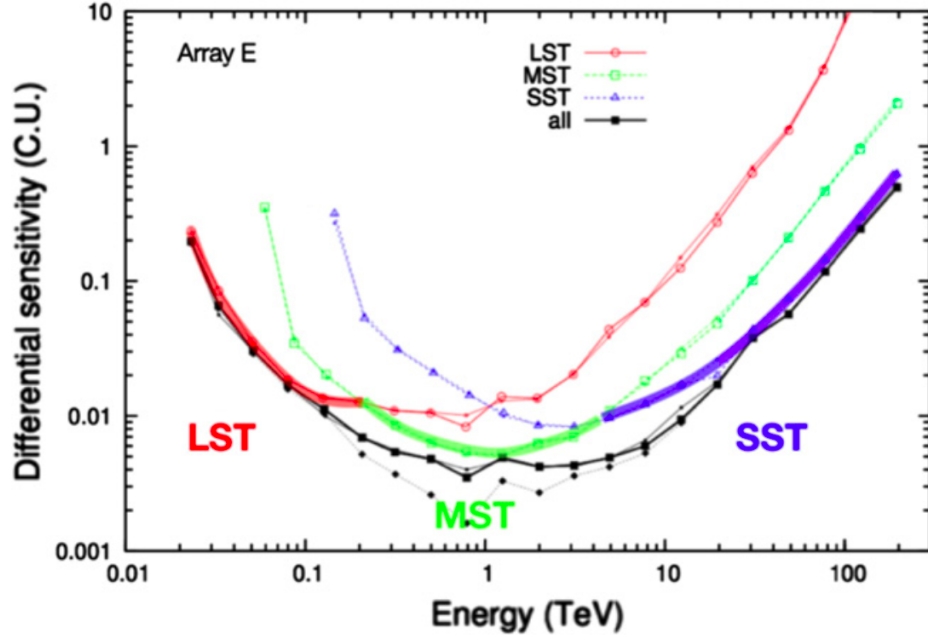


Figure 1.6: The differential sensitivity in units of the flux of the Crab nebula is plotted for the respective energies for the LST (red), MST (green) and SST (blue). The sensitivity in black represents the total sensitivity of all telescope types. Thin lines with small symbols illustrate the limited impact of a reduced dynamic range of the readout electronics (clipped at 1000 photoelectrons). The dashed black line with diamonds, shows the sensitivity if there was no electron background. Image: Acharya et al. (2013)

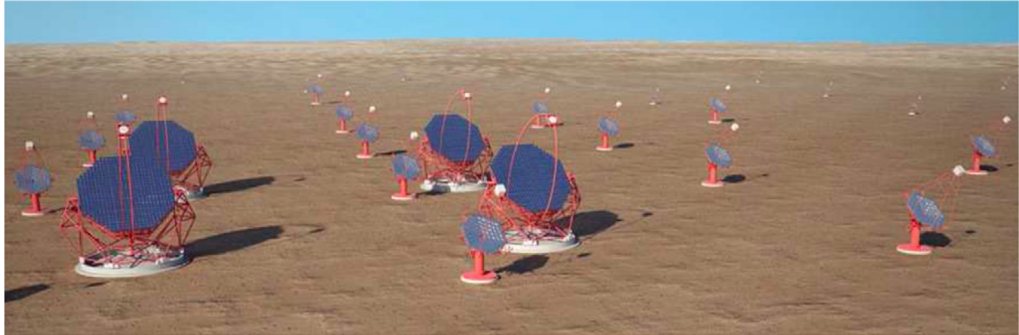


Figure 1.7: An artist's view of a possible configuration of the telescopes of CTA for the southern hemisphere. There are four LSTs, about 30 MSTs and about 50 SSTs placed in an area of several square kilometers. The current (2017) amount of planned telescopes deviates from those numbers. Image: Acharya et al. (2013)

orders of magnitude in energy in the gamma-ray band. Also the angular resolution is expected to increase by a factor of 5 to be of the order of arc-minutes. Another profit of CTA is the public data access which is planned for a ground-based gamma-ray facility for the first time.

1.2.1 The Medium-Sized Telescope

The MSTs will observe in the core energy range of CTA (see 1.6). It is a modified Davies-Cotton telescope and is planned to have a reflector size of 12 m in diameter. At a distance of the focal length of 16 m a photomultiplier tube based camera is located. Figure 1.8 shows the design of a modified Davies-Cotton telescope what is the MST candidate for CTA.

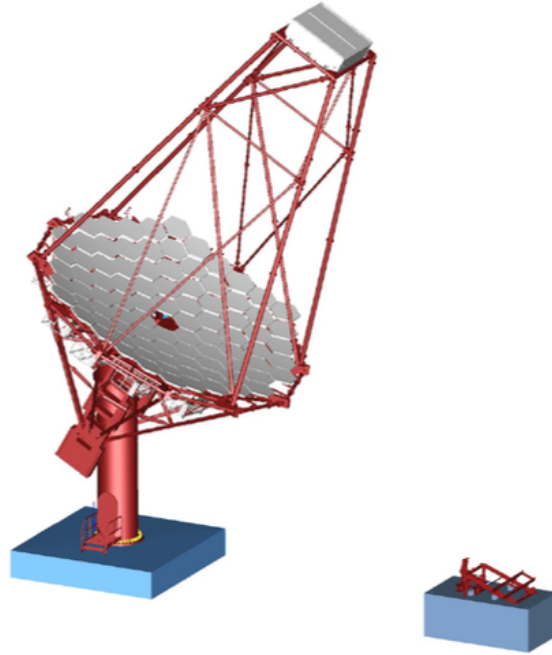


Figure 1.8: Design of a modified Davies-Cotton telescope as MST. The reflector has a diameter of 12 m and the focal length of the telescope is 16 m. Image: Hassan et al. (2015)

There are two different camera designs for the MST. This thesis deals with developments for one of those camera designs called *FlashCam* which is presented in Section 1.3.

1.3 FlashCam

FlashCam is a photomultiplier-tube based camera and is foreseen to be installed on MSTs of CTA. The camera interior is composed of the PDP (**P**hoton **D**etector **P**lane) and the ROS (**R**eadout **E**lectronics **S**ystem) placed in an insulation case with a lid-system, a window in front of the PDP and doors on the rear side (see Figure 1.9). The insulation case has a size of $3 \times 3 \times 1 \text{ m}^3$ containing 1758 pixels (photomultiplier tubes). According to Puehlhofer et al. (2015), FlashCam features the first fully-digital readout system for Cherenkov cameras based on commercial FADCs (**F**lash **a**nalog to **d**igital **c**onverter) and FPGAs (**F**ield **P**rogrammable **G**ate **A**rray).

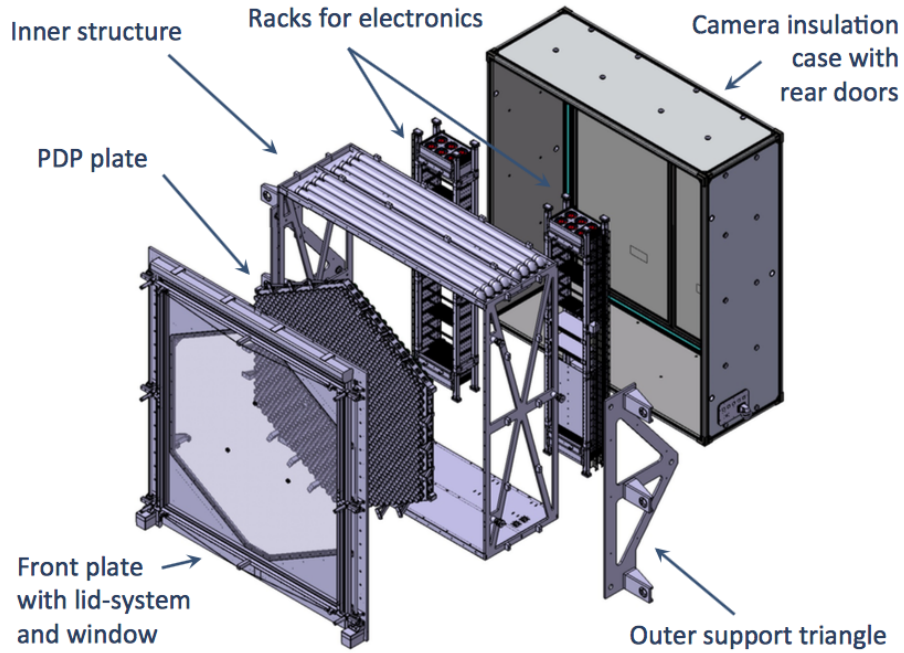


Figure 1.9: Exploded view of the FlashCam camera. The PDP and the ROS are placed in an insulation case with a lid-system and a window near the PDP and doors on the opposite side. Image: Puehlhofer et al. (2015)

- **PDP:** The PDP is divided in PDP modules consisting of 12 photomultiplier tubes each. The high voltage for the photomultiplier tubes as well as the pre-amplifiers and a microcontroller for slow control, monitoring and safety functions are integrated in the PDP modules.
- **ROS:** The analog signals are transmitted from the PDP modules to the ROS via standard CAT-6 Ethernet cables. After the signals are digitized by 12-bit FADCs, they are buffered on FPGAs. The camera trigger is managed by FPGAs as well.

1.3.1 Signal processing

The FlashCam data processing starts with the transmission of the amplified analog signals of the photomultiplier tubes via CAT-6 Ethernet cables to the ROS. There, the signals get digitized and stored in ring buffers in the FPGA. Simultaneously, those digitized data are analyzed in a pre-processing trigger unit. According to Gadola (2013), this unit makes the implementation of trigger classes very flexible, because the trigger classes are implemented in software and can be changed at any time almost on the fly.

The trigger information of several photomultiplier tubes is combined into patches that are handled by one FPGA. A trigger module combines the patch information of seven FADC modules and their neighbouring patches. It issues a trigger signal if the detected amount of light in adjacent patches exceeds a certain threshold. Trigger states of all trigger modules are collected and analyzed by a master distribution module. This master distribution module also distributes the main trigger and the main clock to all boards.

As soon as there is a trigger event, the respective data stored in the ring buffers are read out and transmitted to a camera server. Thereby, a nearly dead time free readout (system) is possible with FlashCam (Gadola, 2013).

1.3.2 Readout electronics

For the FlashCam ROS, motherboards containing a Spartan-6 FPGA from Xilinx were designed. Those motherboards are equipped either with FADC, trigger, or master distribution boards (daughter boards).

- The **FADC board** contains 12 ADC channels interfaced with three RJ-45 connectors. This board is used to convert the analog signals from the photomultiplier-tubes to digital signals.
- The **trigger board** collects trigger information from the FADC modules.
- The **master distribution board** distributes clock and trigger signals.

Figure 1.10 shows a motherboard equipped with two FADC daughter boards. On the bottom left there is a 1 Gbit Ethernet connector for the communication between server software and motherboard. Next to the ethernet connector, there are four LEMO input/outputs for test reasons. For example, they are used for an external trigger signal.

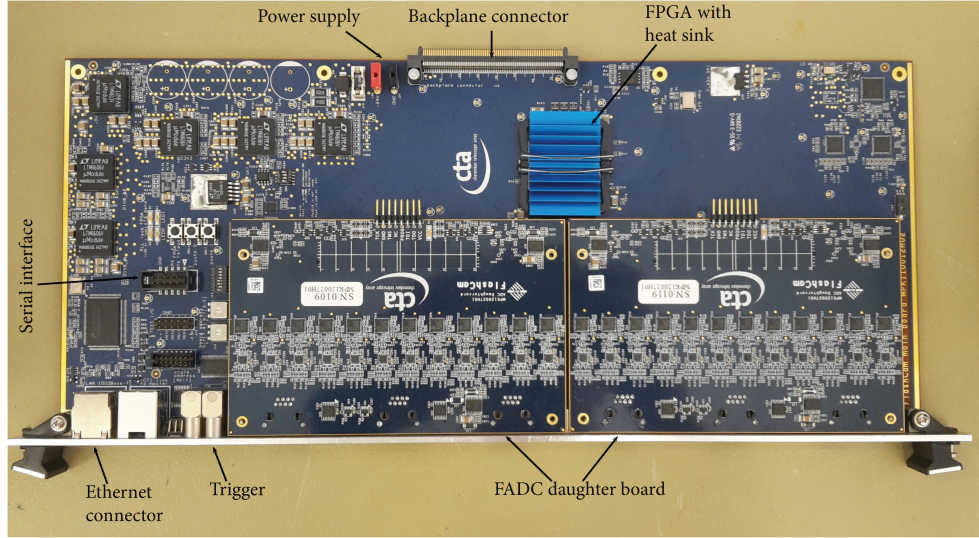


Figure 1.10: Motherboard and two mounted FADC daughter boards of FlashCam ROS. The core of the motherboard is a Spartan-6 FPGA from Xilinx.

The three RJ-45 connectors on each FADC daughter board are used for the analog signal transmission from the PDP to the FADC daughter boards. Each connection transmits up to four analog signals.

The stored data of an event gets (after upsampling to 1 GHz) linearly interpolated and smoothed using moving average⁴. After smoothing the signal, it still has a long tail, which is removed by a deconvolution (pole zero cancellation). After the deconvolution, three more moving averages are applied.

The first part of this thesis deals with the optimization of a test section emulating photomultiplier tube like signals to test FADC modules (motherboards equipped with up to two FADC boards) in large numbers during camera production (see Chapter 2). The second part of this thesis deals with the construction of a darkbox to obtain real photomultiplier-tube signals (see Chapter 3).

⁴The moving average is a statistical method to smooth a data set by averaging a defined interval of measurement points.

Chapter 2

Test section for readout electronics

To test the CTA FlashCam readout electronics, a test section was developed at IAAT¹, see Figure 2.1. Several components of this test section were developed at MPIK²

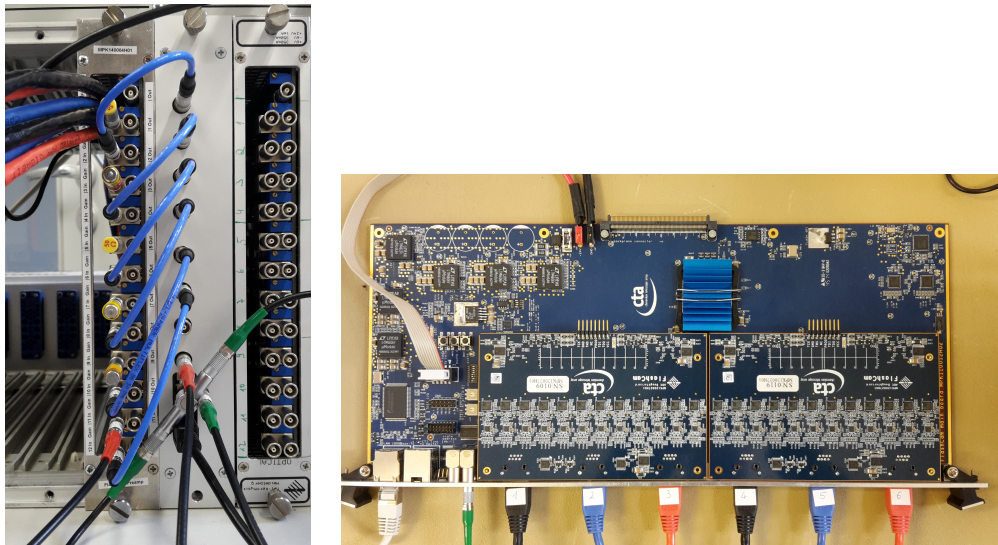


Figure 2.1: Section for functional tests of the CTA FlashCam readout electronics. The pulse generator and the shaper board of the test section are placed in a NIM³ drawer (left figure). The six Cat5 cables (2 in black, blue and red each) transmit the signals from the shaper board to the readout electronics (right figure).

¹Institute for Astronomy and Astrophysics Tübingen

²Max Planck Institute for Nuclear Physics Heidelberg

³Nuclear Instrumentation Module

The test section was developed for large-scale testing during production and is one part of the general testing scheme. Each FlashCam ROS component will be tested in several instances. For example, there is an incoming control for all boards to check for obvious manufacturing errors as well as specific test procedures for all board types to test their functionality. The test section presented in this work is responsible for a functional test of the FADC modules. Hardware and software was developed to emulate PDP-like signals which are used to measure parameters and compare them to predefined acceptance ranges.

The pulse generator, which is presented in Section 2.1, produces a voltage signal with a sharp gradient. The signal of the pulse generator is transmitted to the shaper board (Section 2.2), which differentiates the signal and pass it to the readout electronics. Section 2.3 presents some results of a test measurement with the introduced setup.

The main part of the work described in this thesis was focused on the firmware optimization of the pulse generator. Furthermore, I determined properties of the resulting output signals and I investigated to find appropriate settings for the shaper board to achieve emulated photomultiplier-tube like signals covering an appropriate voltage range for the FlashCam ROS.

2.1 Pulse generator

The core of the pulse generator is a *Spartan-3 FPGA Micromodule* from *Trenz Electronic GmbH*. The FPGA controls eight output channels, one trigger output and handles a trigger input and incoming commands. The timing of the output signals are managed by the trigger signal. When the trigger signal becomes high, each output signal starts its sequence. This sequence is made up of a sharp gradient, a plateau and a decay phase (see Figure 2.2). The sharp gradient is the desired signal what is further processed to create the photomultiplier like signal. This processing (derivation) is sensitive to fast voltage changes. For not manipulating the photomultiplier like signal, there is a constant voltage (plateau phase) before the decay phase starts. During the decay phase, the voltage is decreased slowly enough for not being significant for the processing of the output signal.

Before the decay sequence has been completed, the output signal ignores the trigger signal. As soon as the output signal completed the decay phase, the baseline phase continues until the trigger signal is high.

The hardware interface of the pulse generator is presented and explained in Subsection 2.1.1. The parameters of the output signals and the internal trigger signal are shown in Subsection 2.1.2. In Subsection 2.1.3 the properties of the output signal are presented. In Appendix A, it is explained

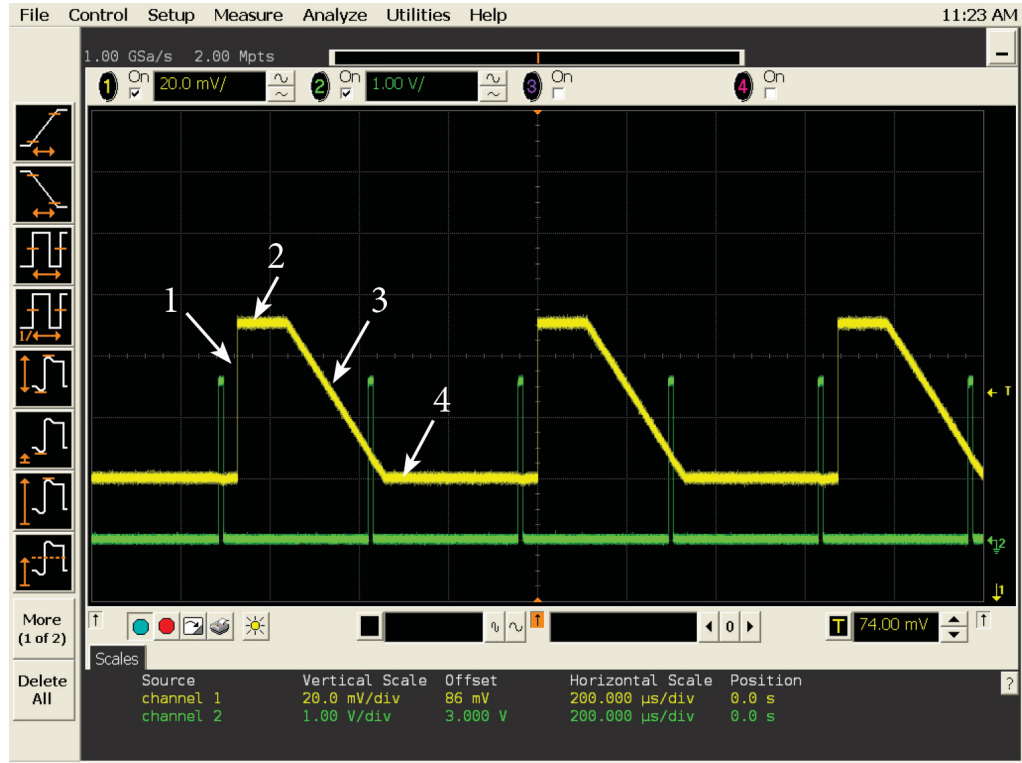


Figure 2.2: Waveform of the trigger and output signal. The internal trigger signal is shown in green (source: channel 2) and one output signal is shown in yellow (source: channel 1). The output signal starts (sharp gradient) after a defined offset time after the trigger flank. The sequence of each output signal is a sharp gradient (1), a plateau (2) and a decay (3), before it returns to the baseline (4).

how to use the USB port to communicate with the FPGA.

2.1.1 Hardware interface

The hardware interface of the pulse generator comprises eight channels for the output signals, one mechanical switch, one trigger input, one trigger output and one USB port (see Figure 2.3) The ports of the output signals and the trigger input and output are realized with LEMO connectors.

- **Channels:** The output signal is controlled by the FPGA and the parameters are adjusted for each channel individually.
- **Mechanical switch:** The mechanical switch can be moved to two positions and sets the pulser to an internal trigger mode (switch down) or an external trigger mode (switch up).



Figure 2.3: Hardware interface of the pulse generator. Beginning from the left side there are the eight output channels, the mechanical switch, the input and output channels for the trigger signals and the USB Mini-B port. The numbering of the output channels starts from the right side with zero and ends at the left side with seven.

Table 2.1: Command list for the pulser channels settings. The available properties, their commands as well as their parameters are listed.

Property	Command	Parameter range	
Attenuator	-chat	Ch. nr. (0 to 7)	binary (0 or 1)
Amplitude	-cham	Ch. nr. (0 to 7)	10 bits (0 to 1023)
Baseline	-chbl	Ch. nr. (0 to 7)	10 bits (0 to 1023)
Voltage high	-chvh	Ch. nr. (0 to 7)	12 bits (0 to 4095)
Voltage low	-chvl	Ch. nr. (0 to 7)	12 bits (0 to 4095)
Plateau duration	-chpd	Ch. nr. (0 to 7)	10 bits (0 to 1023)
Offset	-chos	Ch. nr. (0 to 7)	10 bits (0 to 1023)

- **Trigger output:** If the internal trigger mode is chosen, the signal of the internal trigger is in contact with the trigger output.
- **Trigger input:** If the external trigger mode is chosen, all channels are triggered by exceeding the threshold voltage of $U_{th} \approx 0.9\text{ V}$ of the trigger input. In this mode, the external trigger signal is in contact with the trigger output.
- **USB port:** By using the USB port, commands are sent to the FPGA to set the properties of the internal trigger signal as well as the properties of the channel output signals. The available parameters for the channels are listed in Table 2.1 and for the trigger in Table 2.2.

2.1.2 Properties of the signals

There are seven properties to adjust the output signal as shown in Table 2.1. The voltage of the plateau and the baseline are set with the properties “Amplitude” and “Baseline” in DAC⁴ units. Additionally, there is the

⁴digital to analog converter

Table 2.2: Command list for the internal pulser trigger settings. The available properties, their commands as well as their parameters are listed.

Property	Command	Parameter range
Trigger high	-th	3 bits (0 to 7)
Trigger low	-tl	3 bits (0 to 7)
Trigger high duration	-thd	16 bits (0 to 65535)
Trigger low duration	-tld	16 bits (0 to 65535)

property “Attenuator” which decreases the output voltage by a factor of ten if the attenuator is set to 0. The maximum DAC value for the amplitude of 1023 corresponds to ~ 3.5 V if the attenuator is set to 1 or ~ 350 mV if the attenuator is set to 0. The properties “Voltage high” and “Voltage low” convert the given parameter in mV into the respective values for the attenuator, the amplitude and the baseline. This conversion limits the voltage accuracy to $\Delta U_{t,0} \sim 0.2$ mV if the attenuator is set to 0 ($0 \dots 300$ mV) and $\Delta U_{t,1} \sim 2$ mV if the attenuator is set to 1 (above 300 mV). The “Plateau duration” can adjust the duration of the plateau phase (2) in DAC values, where one DAC value corresponds to $t_{pd} = 216.7$ ns. This value is given by the clock frequency of the FPGA $f_{FPGA} = 60$ MHz and the number of clock cycles implemented for one duration sequence of 13

$$t_{pd} = \frac{13}{60 \text{ MHz}} = 216.7 \text{ ns} \quad . \quad (2.1)$$

This means that for the plateau duration there is a adjustable time range of $T_{pd} = 0 \dots 222 \mu\text{s}$. The property “Offset” defines the time difference between the trigger signal and the start of the signal sequence (sharp gradient). Since the offset property has the same range of ten bits as the plateau duration, the offset can also be set in the range of $T_{os} = 0 \dots 222 \mu\text{s}$.

The properties of the internal trigger signal are adjusted with the commands listed in Table 2.2. With the properties “Trigger high” and “Trigger low”, the amplitude and the baseline of the trigger output signal are set. With the three bits available, those voltages are set in eight steps to $U_t = 0 \dots 3$ V. To start the sequence of an output signal with the internal trigger signal, there is no certain threshold level in the amplitude. This start is managed by the “Trigger high duration” and “Trigger low duration”, which can be adjusted to durations of $T_{td} = 0 \dots 14.2$ ms. By starting the trigger high phase, a flag is set by the FPGA. Whenever this flag is set and the output signal is at the baseline phase, the sequence of the output signals starts. After the trigger high phase finished, this flag is removed and the output signals do not start their sequences until the flag

is set again. For the external trigger mode, there is a threshold level in the amplitude of $U_{\text{th}} \approx 0.9 \text{ V}$.

2.1.3 Properties of the output signals

The properties of the output signals were analysed with the oscilloscope *Agilent infiniiium DSO8104A* with a bandwidth of 1 GHz and a sample rate of 4 GSa/s. The voltages of the output signals (plateau and baseline) as well as the timing of the sharp gradient were measured and analysed.

Voltage measurement

The voltage difference between the plateau and the baseline was measured and is shown in Figure 2.4 for channel 0. For each voltage, 400 000 mea-

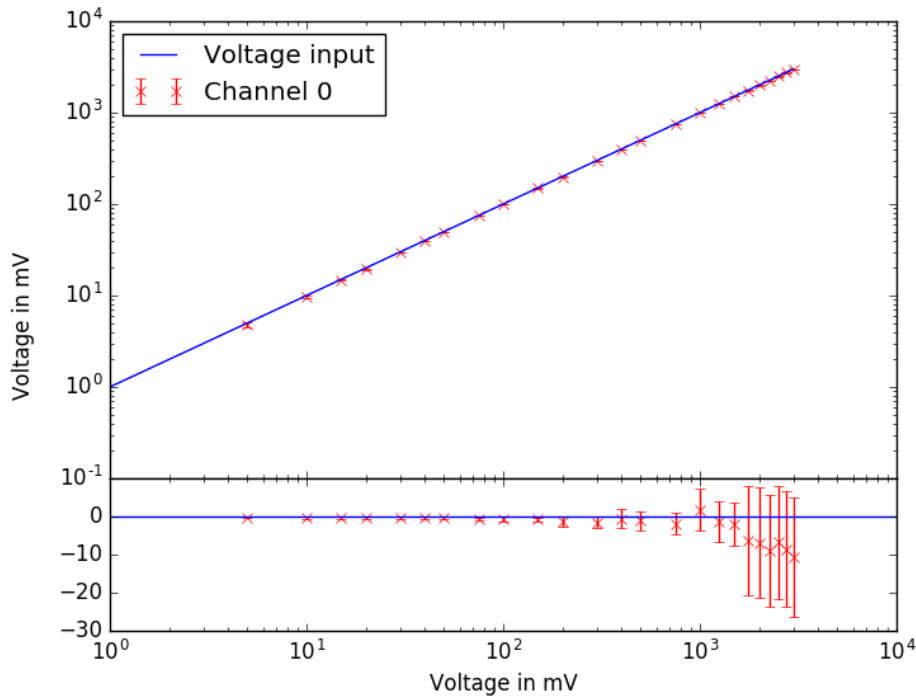


Figure 2.4: Voltage measurement of the output signal of channel 0. In a double logarithmic scale, the measured difference of the plateau and baseline voltage are plotted in the upper graph. In the bottom graph, the deviations to the input voltages are shown. There is an increasing uncertainty and offset for higher voltages. This is caused by the resolution of the oscilloscope.

surement points were taken, where 200 000 points belong to the baseline

and the plateau voltage, respectively. The presented uncertainties in Figure 2.4 are the standard deviations σ . It can be assumed that the noise of the output signal is less than the noise of the oscilloscope of approximately 1 mV (highest sensitivity at low voltages), because the noise level does not change whether the channel is connected to the oscilloscope or not. The increasing noise level for higher voltages is caused by different settings of the oscilloscope. The voltage measurements of the output signals of the other channels looked similar (see Appendix B).

Timing measurement

For the internal trigger mode with a trigger high duration of 20 and a trigger low duration of 5000, the period of the output signal was measured. Furthermore, the rise time of the sharp gradient was measured for a voltage high of 300 mV. This time interval was defined to start at a voltage level of 10% and to end at a voltage level of 90% of the plateau voltage. Those values were measured 1000 times for the channels 0 to 7 and are shown in Table 2.3. The presented periods are consistent except for channel 1. The rise times of all channels are located in the order of the requirement of about 2 ns.

Table 2.3: Results of the timing measurement of the output signals of channel 0 to 7. The Period P of the output signal as well as its rise time t_{rise} are listed.

Ch. nr.	P in ms	ΔP in ns	t_{rise} in ns
0	1.088 081 34	0.11	2.11 ± 0.06
1	1.088 079 69	0.15	2.19 ± 0.05
2	1.088 081 26	0.10	2.09 ± 0.05
3	1.088 081 36	0.09	2.06 ± 0.06
4	1.088 081 41	0.09	2.17 ± 0.06
5	1.088 081 42	0.07	2.09 ± 0.06
6	1.088 081 45	0.07	2.20 ± 0.08
7	1.088 081 46	0.08	2.09 ± 0.06

2.2 Shaper board

The shaper board is a NIM module with 12 input and 12 output channels (LEMO connectors). The input signal of two input channels is distributed on two output channels. Furthermore, those pairs of channels are connected

to RJ-45 connectors. They are used to transmit the shaped signals of the shaper board to the readout electronics using Cat5 cables.

The input channels are connected to 1.5 GHz, ultrahigh speed, high performance, current feedback amplifiers (Analog Devices, 2017). The properties of the shaper board (the voltages of the amplifier connections) are adjusted mechanically using screws. On the interface plane of the shaper board, there are screws for the adjustment of the amplification level of the output signals. The baseline voltage and the clipping height are adjusted by using screws located on the surface of the board.

A screenshot of the oscilloscope *Agilent infiniiium DSO8104A* measuring the output signal of the pulse generator and the shaped signal produced by the shaper board is shown in Figure 2.5. The pulse generator was adjusted to produce a sharp gradient with a voltage difference of 300 mV.

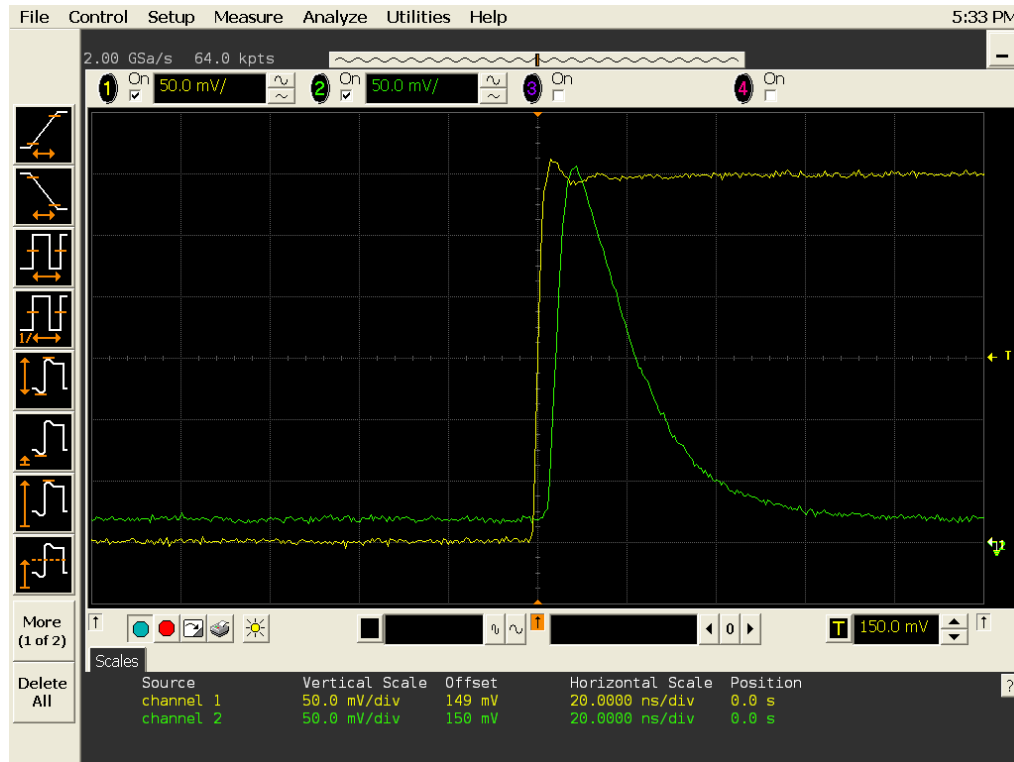


Figure 2.5: Measurement of the output signal of the pulse generator (yellow) and the outgoing signal of the shaper board (green).

The shaped signal has a fast rise time compared to its decay time what is caused by the cutoff frequency a low pass filter. For voltages of the sharp gradient of the pulse generators output signal above an adjustable threshold, the shaped signal clips to a constant value. In this case, the area below the signal contains the amplitude information.

2.3 Test measurement

The presented test section is used to test the FlashCam readout electronics. The purpose is to detect and identify any unusual behavior of the readout electronics. For that purpose, a baseline test (Subsection 2.3.1) and an amplitude test (Subsection 2.3.2) can be performed.

2.3.1 Baseline test

For the baseline test, the pulse generator is set not to generate any signals. However, the readout electronics is analysing the remaining voltage. Starting at a digital baseline level of 100 ADU, the baseline level is increased in steps of 200 ADU until it reaches a baseline level of 2100 ADU. For each baseline level and each FADC channel, data are collected $n = 100$ times and therewith, a rms⁵ value

$$rms = \sqrt{\frac{\sum_{i=0}^n (data[i] - \overline{data})^2}{n - 1}} \quad (2.2)$$

for the baseline is calculated, where *data* is an array containing the data and $\overline{data}$ is the average value of the data set. The rms values are visualized in three dimensional plots.

Figure 2.6 shows the result of a baseline test. The tested components were a motherboard with the number 0013 and two FADC boards with the numbers 0109 and 0119.

To identify the origin of the noise, this baseline test was repeated with an unconnected pulse generator (Figure 2.7) and additionally with an unconnected shaper board (Figure 2.8). Since the mean rms value did not change for the measurement with an unconnected pulse generator, this component does not increase the noise level of the test section. For the measurement with an unconnected shaper board, the rms values are significantly reduced by a value of approximately 0.5 . . . 0.6 LSB. The remaining noise is caused by the readout electronics itself. Figure 2.8 seems to have lower rms values for increasing baseline levels. This behavior cannot be explained.

Nonetheless, the pulse generator can increase the noise of the shaper board if an output signal of the pulse generator has a low voltage level. In this case, a higher gain is needed what increase the noise level of the shaper board.

⁵root mean square

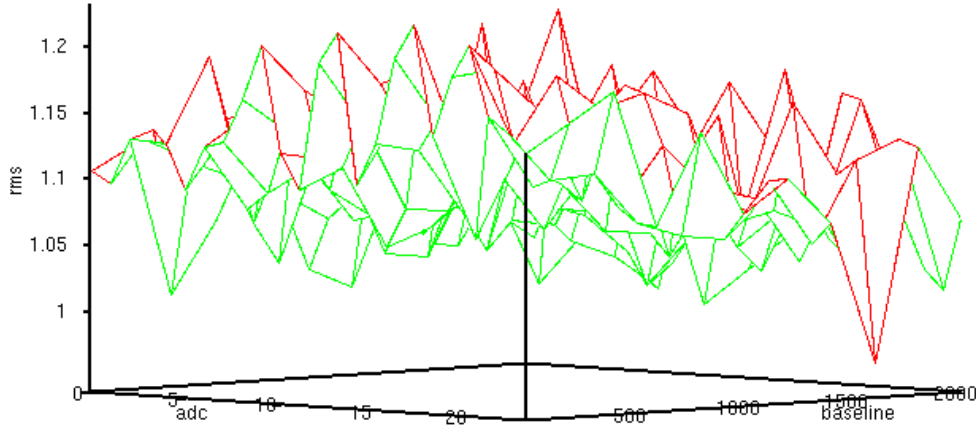


Figure 2.6: Baseline test with connected pulse generator and shaper board. For the rms, there is a mean value of approximately 1.1 LSB (Least Significant Bit) for all FADC channels and baseline levels.

2.3.2 Amplitude test

For the amplitude test, the amplitude of the sharp gradient of the pulse generator is adjusted between 0 V and 3000 V. The signal of the pulse generator for each set voltage is recorded 100 times. The average of those 100 signals is used to calculate up to six amplitude properties.

- **Maximum:** The highest value of the processed signal is defined as the maximum value.
- **FWHM:** The estimated maximum is used to calculate the FWHM (full width at half maximum). Therefore, the two positions of the half maximum in units of time is determined. The difference of these positions is the FWHM.
- **Pole zero:** The pole zero parameter is a result of the pole zero cancellation. The smoothed signal (after using the first moving average) is used to calculate this parameter.
- **Phase adjustment:** The cog (center of gravity) of a signal is calculated for testing timing properties. By increasing the phase in units of time, the cog is expected also to increase by the same value.
- **Integrator:** The integrator is the integral over the signal. Before this value is calculated, the baseline level of the signal has to be subtracted.

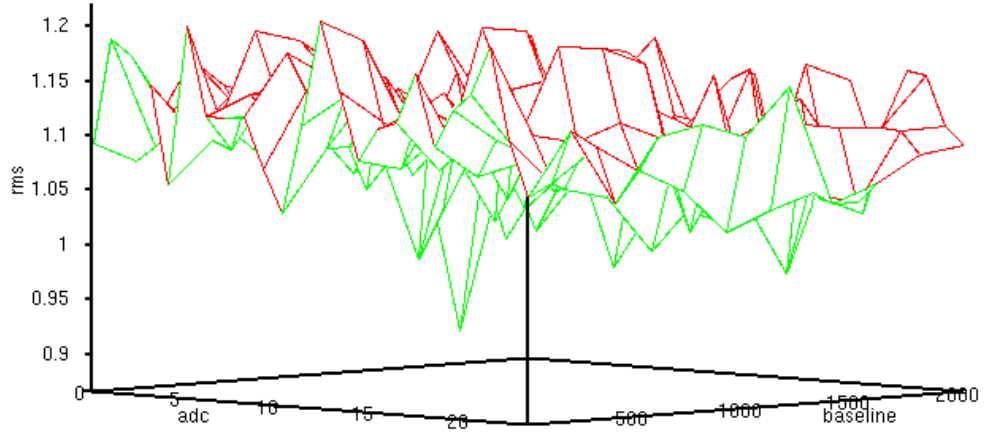


Figure 2.7: Baseline test with unconnected pulse generator. For the rms, there is a mean value of approximately 1.1 LSB for all FADC channels and baseline levels.

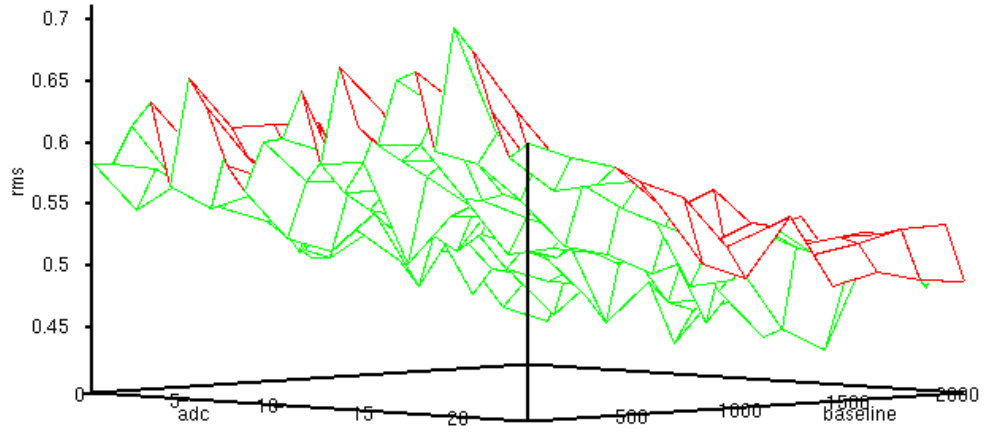


Figure 2.8: Baseline test without any device connected to the FADCs. For the rms, there is a mean value of approximately 0.6 LSB for all FADC channels at low baseline levels. For higher baseline levels, the rms decreases to a value of approximately 0.5 LSB.

- **Integrator/Gain:** The amplitude property integrator/gain is calculated by dividing the integrator by the difference between the plateau and baseline voltage of the pulse generator.

Appendix C shows the results of an amplitude test for one motherboard equipped with two FADC boards. The maximum, FWHM, pole zero, phase

adjustment and integrator are convenient properties to test the ADC channels. Intervals are defined in which the values of each ADC channel have to be inside for each property.

The pulse generator is now ready to be operated in the test section for FlashCam readout electronics. It supplies reliable voltages and timing properties. For mass testing of the readout electronics, further upgrades to the test section should be accomplished. For example, a fast connecting and disconnecting of ethernet cables on the readout electronics should be realized.

Chapter 3

Construction of a darkbox setup

The second part of this thesis concerns the construction of a darkbox setup. The darkbox is opaque for optical light and therefore it is suitable for operating photomultiplier tubes. Figure 3.1 shows the CAD¹ design of this darkbox setup.

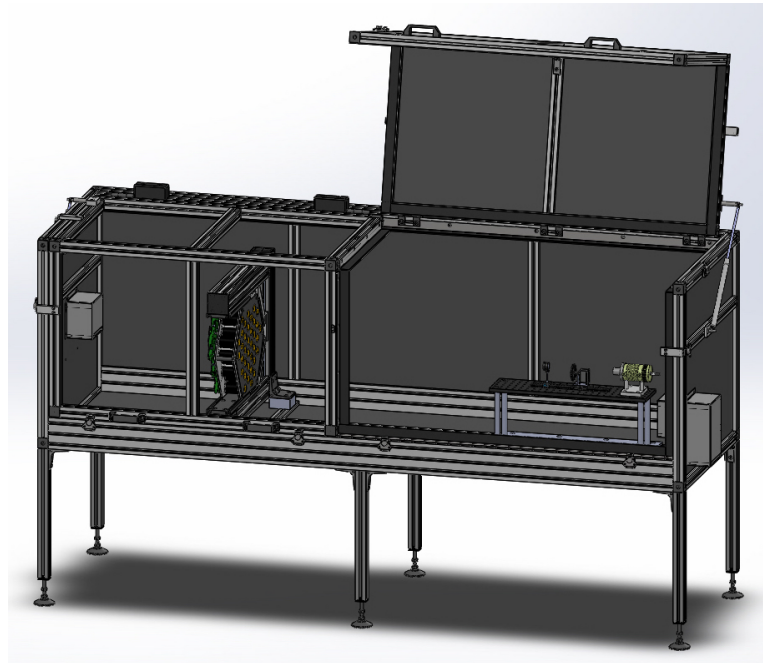


Figure 3.1: Design of a darkbox setup for the operation of photomultiplier tubes (left side) equipped with the an optical setup composed of a laser, a filter wheel and a diffuser (right side).

¹computer-aided design

It is a lab-based debugging platform during the camera operation in the field. Furthermore, tests for a FlashCam field calibration device and calibration procedures can be realized. The darkbox is also suitable for testing other components for future upgrades, for example silicon photomultipliers. The design of the darkbox setup is presented in Section 3.1.

3.1 Design of the darkbox setup

The design of the darkbox setup (see Figure 3.1) is strongly based on developments of the FlashCam group at the Friedrich-Alexander University of Erlangen-Nürnberg, but with modifications of the opening system of the darkbox, the mounting of the optical components and the detector mountings. The darkbox setup is composed of the darkbox itself (see Subsection 3.1.1), optical components (see Subsection 3.1.2) and detectors (see Subsection 3.1.3).

3.1.1 Darkbox

Figure 3.2 shows the unequipped darkbox design. The darkbox has an outer size of $80\text{ cm} \times 80\text{ cm} \times 248\text{ cm}$ standing on six feet with a height of about 60 cm. The exact height is adjusted using threads of the feet.

The majority of the components of the darkbox are standard products offered in industry, but there are also unique components which were made by the workshop of IAAT. The main components of the darkbox are

- **profiles** of the **series 40** offered by the *Maschinenbau Kitz GmbH*. Those profiles are the framework of the darkbox. They are mounted with angle connections, tension connections or corner connections.
- **black PVC plates** hold by the profiles. Their main task is to avoid light to come in or come out of the darkbox.
- **hinges, gas springs** and **butterfly locks** to realize the opening system of the darkbox. The front is fixed to the top of the darkbox whereby it is opened as one unit. By opening or closing butterfly locks, the box is opened either on the right side as it is shown in Figure 3.2 or both sides are opened at once. Because of angle plates, the box can not be opened on the left side only. Further butterfly locks are used to apply pressure on the opening system to increase light tightness. The gas springs mounted on the left and right side of the box support the opening and closing of the darkbox and keep it in the opened position.

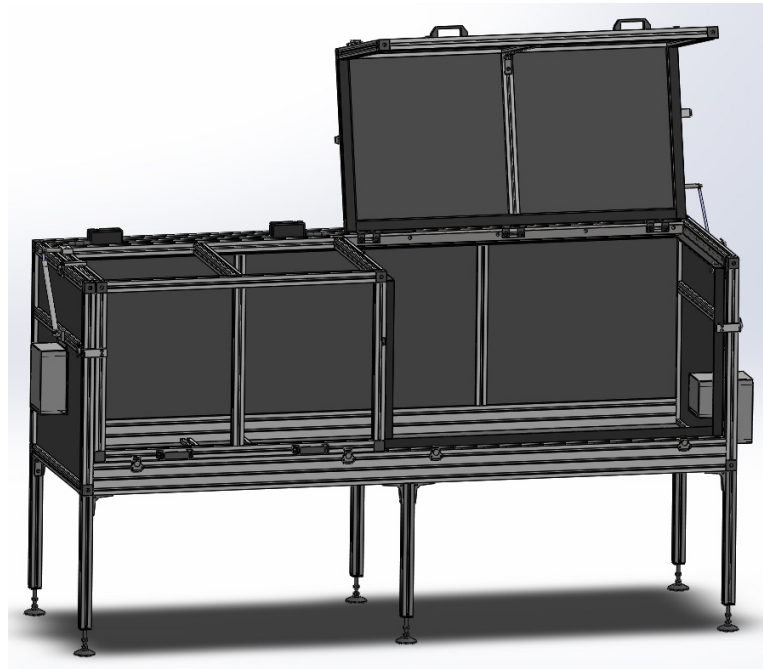


Figure 3.2: Design of an opaque darkbox. The box is opened at the right side while the left side is closed.

- **cable boxes** on the left and the right side of the darkbox. Therewith, wires can be installed to communicate with electrical components inside the darkbox while it is closed. There are small holes in the pvc plates as well as in the boxes to minimize the light coming in and out of the box. The remaining apertures are isolated afterwards using opaque foil.
- **neoprene mats** to increase the light tightness of the darkbox. They are mounted on angle plates located at the front and the top of the box where it can be opened.
- **velvet adhesive foil** to decrease the light reflectivity inside the box. The inner surface of the darkbox is completely covered with this foil, because scattered laser light could cause unpredictable background in the detectors.
- **snap-action switch** for safety reasons. While the darkbox is opened, high voltages as well as the laser have to be deactivated. To be sure that those components are deactivated, they are connected to a snap-action switch installed on the right opening side. As soon as the darkbox gets opened, the power supply of the laser is switched off.

In principle, this darkbox could be equipped with various optical components and detectors. The installed optical components of the current setting are presented in Subsection 3.1.2 and the available detectors are presented in Subsection 3.1.3.

3.1.2 Optical components

In the current setting of the darkbox, beginning from the right there are a laser, a filter wheel adjustable by a servo motor and a diffuser (see Figure 3.3). Except for the laser, the optical components are mounted with rail carriers on an optical rail. The optical rail itself is mounted on an aluminum breadboard and the breadboard is situated on an enhancement to be located close to the center of the darkbox cross section.

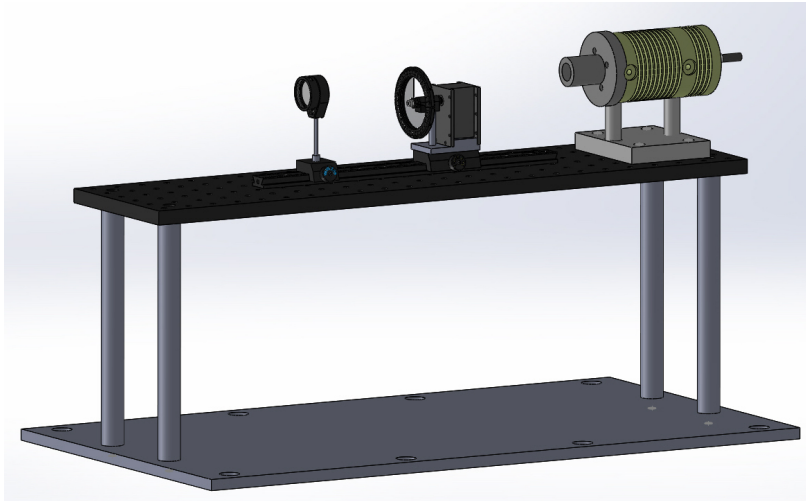


Figure 3.3: Design of the optical components inside the darkbox. Beginning from the right, there are a laser, a filter wheel adjustable by a servo motor and a diffuser.

The Laser

The installed laser with the name *LDH-D-C-405* from the *PicoQuant* LDH (Laser Diode Head) series is a cooled dual mode laser with a wavelength of (405 ± 10) nm. The laser is operated either in a cw (continuous wave) mode or in a pulsed mode with an adjustable pulse frequency. The power properties of the laser are listed in Table 3.1. The safety class number of this laser is stated to be 3B². Since the laser can only be operated when

²Lasers of the safety class number 3B have a maximum power of 500 mW in a cw mode. If the unscattered laser beam of this safety class number points into a humans

Table 3.1: Properties of the *LDH-D-C-405* laser. According to PicoQuant GmbH (2017b), the power of the cw mode as well as the pulse width and the average power for a narrow and a wide pulse of the pulsed mode are listed.

Laser	LDH-D-C-405
CW power	50 mW
narrow pulse	
Pulse width (FWHM)	< 50 ps
Average power 40 MHz	1 mW
wide pulse	
Pulse width (FWHM)	< 500 ps
Average power 40 MHz	3 mW

the darkbox is closed because of the snap-action switch, there is no danger for nearby persons.

As shown in Figure 3.3, the laser is equipped with an attachment. This attachment reduces scattered light in the darkbox and therewith it reduces background for the detectors. The attachment is mounted on the front of the laser casing using screws. Furthermore, the laser is mounted on two cylinders to a metal plate. Because of a wide drilling in the metal plate for the left cylinder, the direction of the laser beam can be adjusted horizontally.

The power connection for the laser is located outside of the box. A cable from the laser is placed to go through the cable boxes on the right side of the darkbox to the power supply. This is a picosecond pulsed diode laser driver with cw capability called *PDL 800-D* from *PicoQuant*. According to PicoQuant GmbH (2017a), the *PDL 800-D* has a crystal locked internal oscillator with 80 MHz and 1000 kHz selectable base frequencies. Therewith, the repetition frequencies listed in Table 3.2 are realized.

With the external trigger input of *PDL 800-D*, frequencies from 10 Hz up to 80 MHz are achieved. For this mode, there is a delay time between the trigger input signal and the optical output of (35 ± 5) ns with a jitter of < 20 ps.

PDL 800-D has a remote interlock that is connected with the snap-action switch of the darkbox. For an opened darkbox, the remote interlock is open and therewith the power supply for the laser is deactivated. The

eye, this can cause eye damage. A scattered laser beam of this safety class number can also cause eye damage.

Table 3.2: Repetition frequencies of *PDL 800-D*. The repetition frequencies are realized by reducing the base frequencies (80 MHz and 1000 kHz) by defined factors between 1 and 32.

Reduction factor	Repetition frequency in MHz	Repetition frequency in kHz
1	80.0	1000.00
2	40.0	500.00
4	20.0	250.00
8	10.0	125.00
16	5.0	62.50
32	2.5	31.25

laser is activated by a closed remote interlock when the darkbox is closed.

The continuous nd filter wheel

To realize an individual light intensity without changing the pulse form of the emitted light, a continuous filter wheel from *Thorlabs* is installed after the laser (see Figure 3.3). It is an nd³ filter with a wavelength range of 350...700 nm and an optical density of 0...4.0.

The filter wheel is connected to the servo motor *Dynamixel MX-28AT Robot Servo* from *noDNA* to adjust the position of the filter wheel and therewith the optical density. The servo motor is controlled by the *FlashCam Calibration Controller*, a device from MPIK based on an *Arduino Leonardo Ethernet 2 Arduino Shield Development Board*. There are three Python scripts to handle the servo motor.

- **servctl_discover:** This script looks for an *Arduino Leonardo Ethernet 2 Arduino Shield Development Board* connected to a local network by running this script without any parameters. This Python script is also able to change the ip address of the *FlashCam Calibration Controller* by running the script with the parameters *-ip* and the new ip address of the device.
- **servctl_ping:** The *FlashCam Calibration Controller* is pinged by using this script with the ip address of the device as parameter. This is useful to check the reachability, especially after changing the ip address.

³An nd (neutral-density) filter reduces the intensity of light independent of its wavelength.

- **servoctl_move:** The servo motor is controlled using this script with the ip address of the *FlashCam Calibration Controller* and the desired position of the servo motor as parameters. The position of the servo motor is adjusted with values between 0 and 4095, which represents one complete cycle rotation. To simplify the adjustment of the filter wheel position, there is a script *servoctl_setatt.sh* which automatically provides the ip adress and translates the arbitrary chosen numbers 0 to 1000 to the respective filter wheel position. Thereby the number 0 represents a position without attenuation and the number 1000 represents a position with highest attenuation.

For further information how to use one of those scripts, the parameter *-h* can be typed.

The diffuser

According to Figure 3.3, a diffuser *ED1-C20-MD* from *Thorlabs* is mounted after the filter wheel. The diffuser has a transmission of about 90 % for 380...1100 nm wavelength and a divergence of 20° for collimated light with a wavelength of 633 nm⁴. The diffuser itself is attached on an appropriate lens mount from *Thorlabs* that is mounted at a cylinder adjustable in height.

3.1.3 Detectors

The developed darkbox is a convenient environment for testing optical sensitive detectors. Within the scope of the FlashCam project, the darkbox was designed for operating photomultiplier tubes, but basically different types of optical detectors can be operated there. To quantify the flux properties inside the darkbox, a photodiode and a PDP module were used.

The photodiode

The photodiode *PS7-5b TO* from *First Sensor* is optimized for blue light and therefore it is a sensitive detector to observe the laser light with the wavelength of (405 ± 10) nm. Figure 3.4 shows the photodiode and a mounting for the photodiode in the detector plane of the darkbox. The characteristics of the photodiode *PS7-5b TO* are listed in Table 3.3. The photodiode was connected to the *Model 2657A High Power System Source-Meter Instrument* from *Keithley Instruments*. This device has a source feature with a voltage supply from 5 mV to 3030 V and a current supply

⁴The light of the laser with (405 ± 10) nm wavelength may cause nominal variance of divergence.

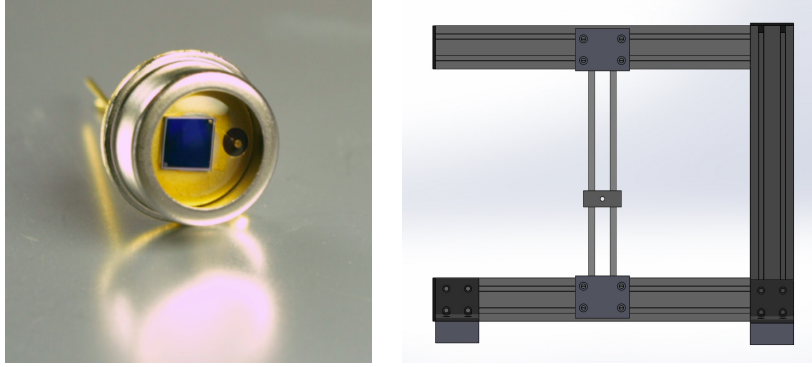


Figure 3.4: The photodiode *PS7-5b TO* (left, Image: First Sensor AG (2013)) and its mounting (right).

Table 3.3: Properties of the photodiode *PS7-5b TO*. The values were taken from First Sensor AG (2013).

Parameter	Value
Active area	7.1 mm^2
Fully depleted	3.5 V
Max reverse voltage	30 V
Dark current at 3.5 V	0.04 nA
Responsivity at 405 nm	0.23 A/W

from 30 fA to 120.12 mA and a measure feature with a voltage sensitivity from 1 mV to 3030 V and a current sensitivity from 20 fA to 120.12 mA (Keithley Instruments, 2012). The features of this instrument were used to realize a reverse voltage of the photodiode of 20 V and to measure the resulting photodiode current.

The mounting of the photodiode (see Figure 3.4 right) was used to place the photodiode at different positions in the detector plane of the darkbox to check the homogeneity of the laser cone. The results of this measurement are presented in Section 3.2.

The photomultiplier tubes

The photomultiplier tube *R12992-100* from *Hamamatsu photonics* is used as detector in the FlashCam camera. Table 3.4 shows properties of the photomultiplier tube *R12992-100*. 12 photomultiplier tubes are combined to one PDP module (see Figure 3.5).

Up to three PDP modules can be mounted in the darkbox using the designated PDP module mounting. Figure 3.6 shows the front and back

Table 3.4: Properties of the photomultiplier tube *R12992-100*. The values were taken from Hamamatsu Photonics (2017).

Parameter	Value
Spectral response	300 nm to 650 nm
Wavelength of maximum response	400 nm
Minimum effective area	ø 30 mm
Anode sensitivity	4.4×10^3 A/W
Anode dark current	5 nA
Anode pulse rise time	2.3 ns

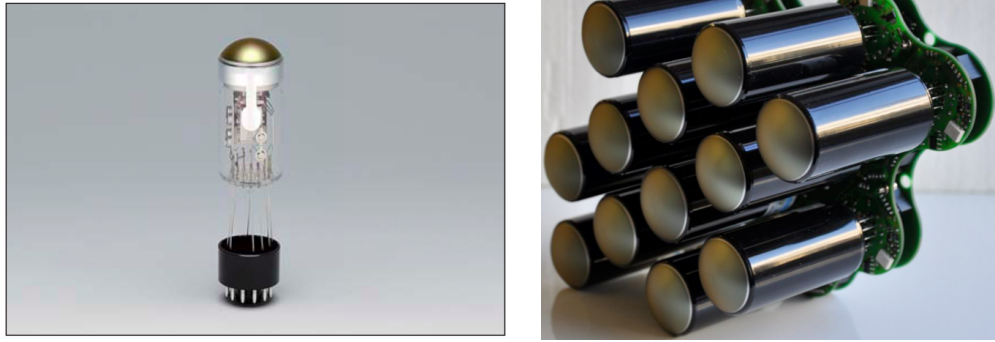


Figure 3.5: The photomultiplier tubes for the FlashCam camera. On the left figure there is a single photomultiplier tube (Image: Hamamatsu Photonics (2017)). On the right figure there are 12 photomultiplier tubes combined to one PDP module (Image: Bauer et al. (2012)).

side of the PDP module mounting equipped with three PDP modules. The PDP modules are inserted from the back side into two holding plates. Those plates are hold by rails mounted on the three profiles. Those plates can be taken out of the mounting for a more comfortable equipping of the darkbox setup with PDP modules. Within the scope of this thesis, the design but not the construction of this mounting could be finished because of the high workload of the workshop group.

The communication with a PDP module and its power supply is realized via CAN cables. There is an initialisation script called *initsetup* for loading PDP control functions and setting parameters to default values. The PDP control functions

- | | | |
|----------------|-----------------|---------------------|
| a) PDPGetAll | b) PDPGetGain | c) PDPGetHV |
| d) PDPGetHVAll | e) PDPGetHVBits | f) PDPGetHVCcurrent |

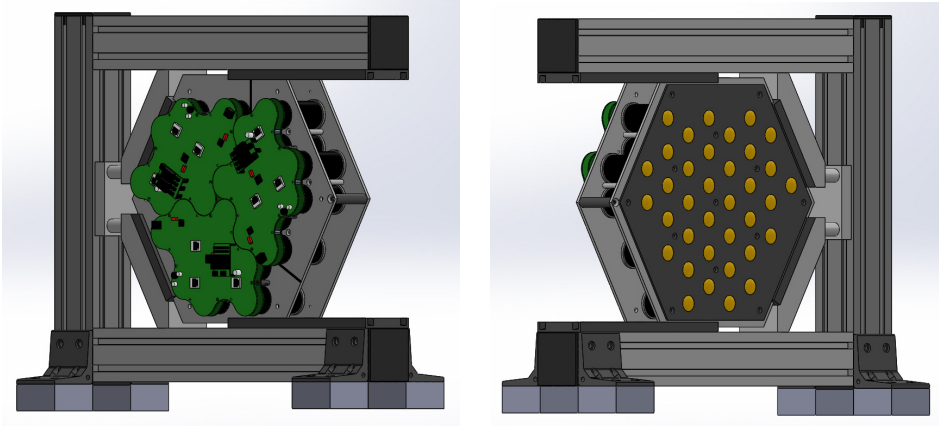


Figure 3.6: The PDP module mounting equipped with three PDP modules. The left figure shows the back side of the PDP module mounting and the electronics of the PDP modules. The right figure shows the front side of the PDP module mounting and the effective areas of the photomultiplier tubes.

- | | | |
|-------------------|--------------------|--------------------|
| g) PDPGetTemp | h) PDPGetTripLimit | i) PDPGetTripTime |
| j) PDPGetVMinus | k) PDPHVOff | l) PDPHVOn |
| m) PDPSetAll | n) PDPSetGain | o) PDPSetHV |
| p) PDPSetHVAll | q) PDPSetHVBits | r) PDPSetTripLimit |
| s) PDPSetTripTime | t) PDPSetVMinus | |

realize to set and read several parameters of the PDP modules and the photomultiplier tubes individually.

3.2 Measurement results

The presented detectors (see Subsection 3.1.3) were used for measuring flux properties of the constructed darkbox setup. A homogeneity measurement at the detector plane of the laser cone was performed with the photodiode, which is presented in Subsection 3.2.1. In Subsection 3.2.2, the results of a light tightness measurement using a PDP module are presented.

3.2.1 Homogeneity measurement

For the homogeneity measurement of the laser cone, a distance between the diffuser and the detector plane of $d = 120$ cm was adjusted. For this distance, nearly the complete area enclosed by the mounting profiles (see Figure 3.4 right) is exposed. The laser was operated with highest intensity in cw mode and in a pulsed mode with 80 MHz repetition frequency also with highest intensity. For both modes, the filter wheel was in a position to realize an optical density of 0.

The *Model 2657A High Power System SourceMeter Instrument* was adjusted to provide the photodiode with a reverse voltage of 20 V and to measure with a NPLC (Number of Power-Line-Cycles) of 10. The distance of two measurement points of the photodiode in each direction was defined to be 3 cm. The origin of the chosen coordinate system was defined to be located at the inner edge of the darkbox. Figure 3.7 shows the results of the homogeneity measurement with the cw laser mode.

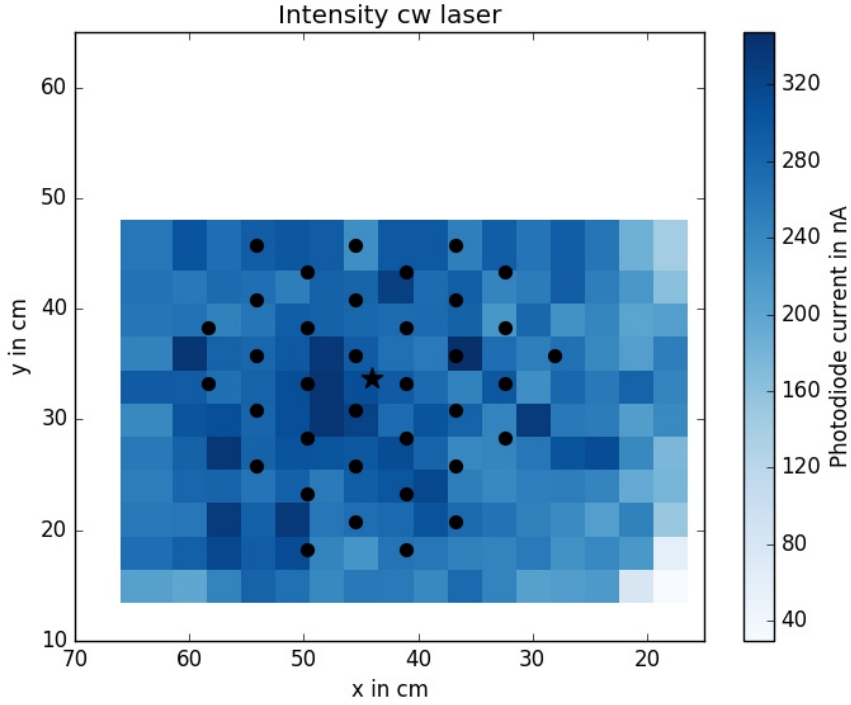


Figure 3.7: Homogeneity measurement with cw laser at highest intensity. The black star represents the position of the laser beam and the black dots represents the positions (not the size) of the photomultiplier tubes of the PDP mounting.

The pixel size (the active area of the photodiode) is enlarged to the

distance of two measurement points to obtain a better visibility of the photodiode currents. On the bottom right and top right corners of this figure, the effect of the edges of the laser cone can be seen. The positions of the photomultiplier tubes are completely exposed by the light cone, but there is a range of the photodiode current of about 200 nA up to 350 nA. Since the photodiode current is proportional to the intensity of the incident light, this results in intensity variations in the order of factor 2.

Figure 3.8 shows the results for the same measurement, except for the laser what was chosen to operate in a pulsed mode with a repetition frequency of 80 MHz. It can be seen that there are no considerable differences between the homogeneity with the cw and the pulsed laser mode.

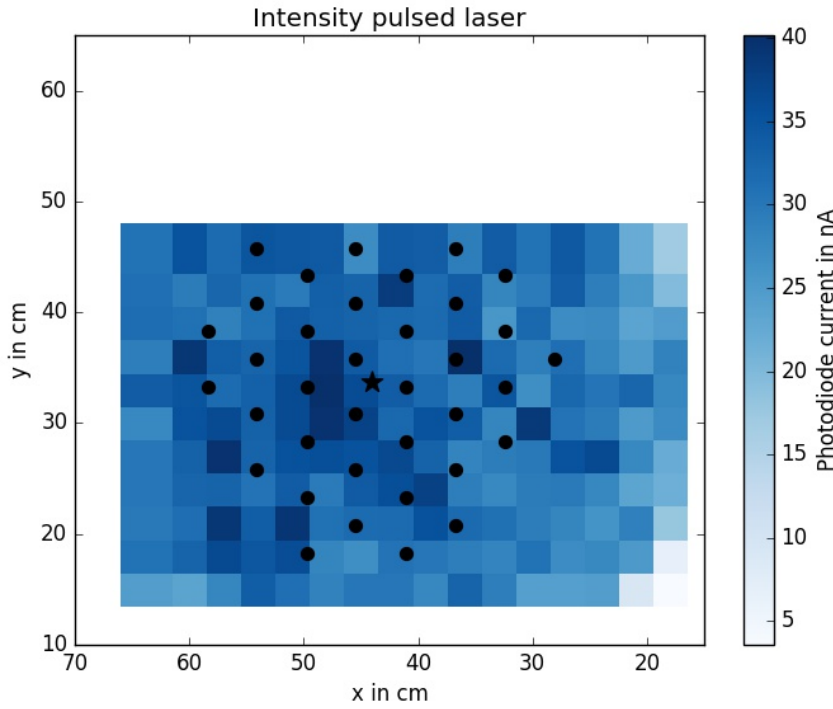


Figure 3.8: Homogeneity measurement with pulsed laser at highest intensity with a repetition frequency of 80 MHz. The black star represents the projected position of the laser beam and the black dots represents the positions (not the size) of the photomultiplier tubes of the PDP mounting.

The presented inhomogeneity of the photodiode measurement can be explained. It is caused of fine structures of the diffuser which results in larger structures at the detector plane with a usual size of a few millimeters. Since the photodiode has an active area of $2.66 \text{ mm} \times 2.66 \text{ mm}$, the structures at the detector plane cause the observed variations of the photodiode current.

To quantify those structures, a picture of the detector plane was taken with the camera *Canon EOS 1200D* with an equipped *Canon EF-S 18-55mm 1:3,5-5,6 IS II* objective and an adjusted focal length of 55 mm. Therefore, two sheets of DIN A3 white papers were attached at the mounting profiles, to cover the complete area in between. The camera was placed directly under the optical components to take a raw image. Due to a timing trigger, the darkbox could be closed before the camera took the image. The raw data were used for an analysis of the structure using Python.

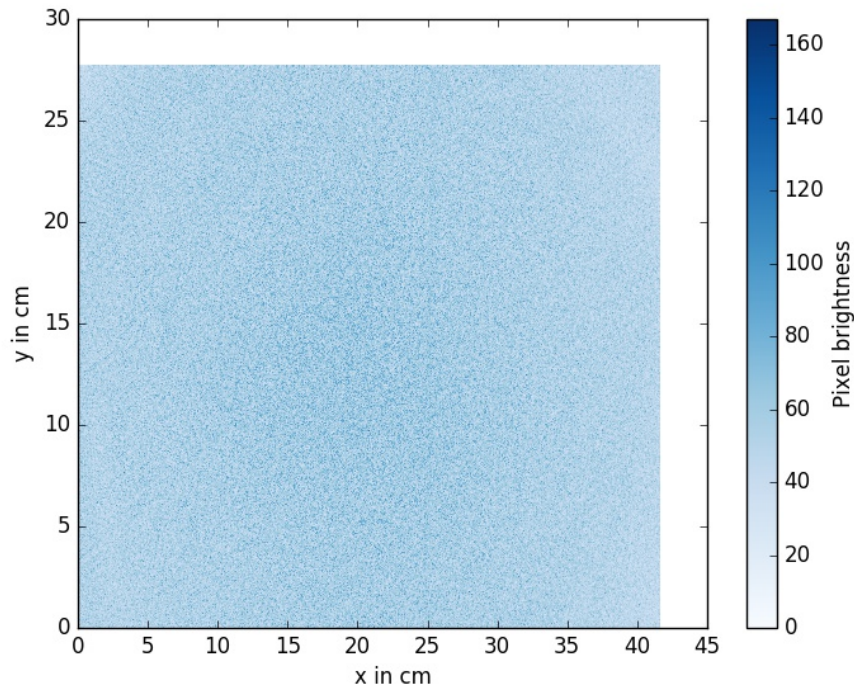


Figure 3.9: Pixel structure of the homogeneity measurement. The brightness of each pixel is shown in this plot. Variations in the brightness from 0 to 160 can be seen.

Figure 3.9 shows the pixel brightness of the taken picture, an area centered around the position of the laser beam. The brightness of the pixels has a range from 0 to 160. It was estimated that one camera pixel covers a size of $0.08 \text{ mm} \times 0.08 \text{ mm}$. To simulate the photodiode measurement, the brightness of 33×33 pixels were averaged. This area is close to the active area of the photodiode. The resulting averaged brightness is shown in Figure 3.10. Besides a systematic decrease of the brightness to outer pixels at larger scales, deviations of the order of 30 % for neighboured pixels are present. This is in a good agreement with the results of the photodi-

ode measurement. Furthermore, there is a bright row at $x = 25$ cm what is caused by an overlap of the two attached paper sheets at the detector plane.

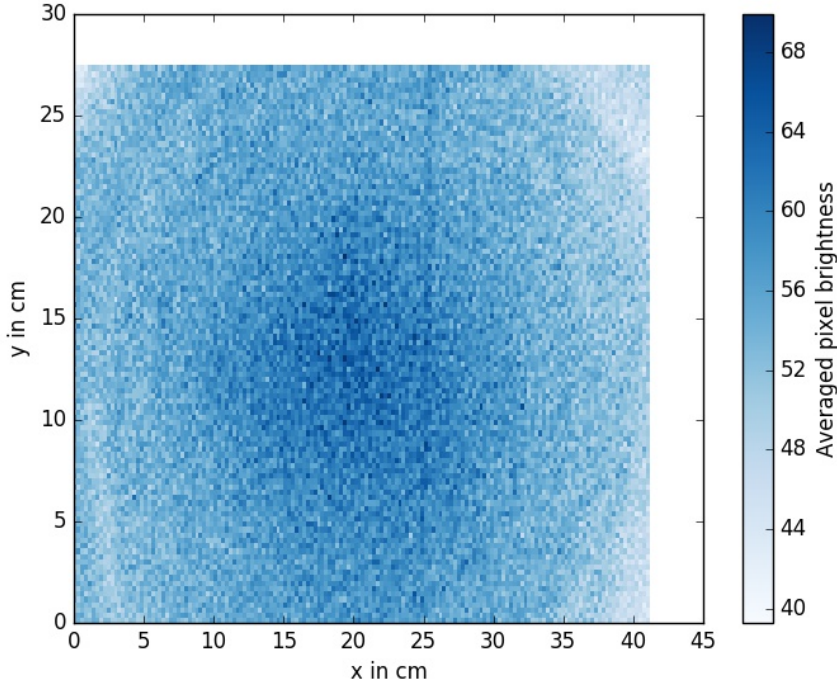


Figure 3.10: Averaged pixel structure of the homogeneity measurement. The brightness of 33×33 pixels were averaged to test a homogeneity over larger scales. The averaged pixels have a size of $2.64 \text{ mm} \times 2.64 \text{ mm}$.

Figure 3.11 shows the averaged brightness of 150×150 pixels, which is equal to an area of $12 \text{ mm} \times 12 \text{ mm}$. The deviations of neighboured pixels of the order of 30 % vanished for those areas. Only the systematic effect of decreasing brightness at outer pixels remains. Since the photomultiplier tubes have a minimum effective area with a diameter of 30 mm (see Table 3.4), the structures at the detector plane is not an issue for measurements with PDP modules.

3.2.2 Light tightness measurement

The light tightness of the darkbox was measured using one FlashCam PDP module. The PDP module was placed in the bottom center of the detector plane. With a set high voltage of 800 V, each photomultiplier was operated in a single operation mode. This was realized using the *PDPSetHVBits*

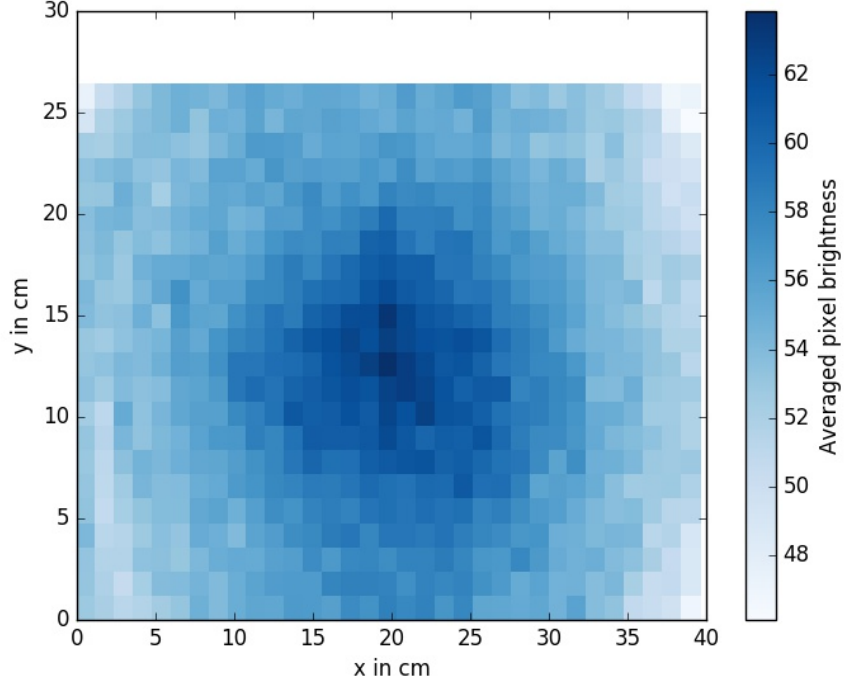


Figure 3.11: Averaged pixel structure of the homogeneity measurement. The brightness of 150×150 pixels were averaged to test a homogeneity over larger scales. The averaged pixels have a size of $12 \text{ mm} \times 12 \text{ mm}$.

function which enables or suppresses the high voltage supply for each photomultiplier tube individually. The *PDPSetHVBits* has a parameter to address the requested PDP module⁵ and a 12 bit binary parameter to set the high voltage of each photomultiplier of the chosen PDP module. For example, the command

$$\text{PDPSetHVBits } 0 \ 7 \quad (3.1)$$

enables the high voltage for the photomultiplier tubes 0, 1 and 2 of the PDP module with the address 0. The other photomultiplier tubes of this PDP module are not supplied with a high voltage.

After setting the high voltages, the trigger rate measurement can be started. For this measurement, the trigger rate was directly estimated using only one FADC module but not a trigger module. Therefore, the crate with the FlashCam ROS has to be booted first. This is done with the command

$$\text{./efbprun ./fwl-fc250b -ei enp1s0 -et efb0 -ps 2 -b 21} \quad , \quad (3.2)$$

⁵In case of a single operating PDP module this parameter value has to be set to 0.

whereby the ethernet interface is set using *-ei* and the ethernet type is set using *-et*. With *-ps* and *-b*, the prom slot and the boot slot of the FPGA are chosen.

With the command

$$./efbprun ./test-fc250b -ei enp1s0 -et efb0 -a 21 -athr 10 -sd 20 \quad , \quad (3.3)$$

the FlashCam ROS triggers single photon signals, where the base address of the module is set with *-a*, the trigger threshold is set with *-athr* and *-sd* sets the data storage delay. The trigger threshold of 10 ADU is approximately equal to one PE (photoelectron).

The first measurement showed a trigger rate between 2000 events/s and 3000 events/s. This was mainly caused of leaking apertures located at the mounted angle plates of the opening system in the middle of darkbox. Those apertures could be tighten by increasing the pressure applied by the butterfly locks and using additional velvet adhesive foil inside the darkbox. Table 3.5 shows the averaged trigger rates of the single photomultiplier tubes and the measured high voltages during the operation after optimizing the light tightness of the darkbox.

Table 3.5: Trigger rate of the 12 PMTs of one PDP module during operation in the darkbox without any light source. The stated trigger rates are averaged values of 100 s measurement time.

PMT	Voltage in V	Trigger rate in events/s
0	822	6
1	822	5
2	826	4
3	821	5
4	823	5
5	820	4
6	819	9
7	820	7
8	816	5
9	820	4
10	820	4
11	822	4

The trigger rate of 62 events/s for all photomultiplier tubes of the PDP module seems to be dark counts (for example caused by radioactive decays or muons) instead of real photon events. The trigger rate does not

decrease with an additional covering of the effective area of the photomultiplier tubes.

The presented results are satisfying in respect of the construction goals of the darkbox setup. The light tightness measurement showed that the darkbox is a suitable environment for operating light sensitive detectors. In combination with the optical components, the darkbox setup can be used to expose detectors with variable intensities. For example, a miniature FlashCam is realized with this lab setup.

Chapter 4

Summary and conclusion

This thesis consists of two substantial parts. The first part is the optimization of a pulse generator for the testing of CTA FlashCam readout electronics. The second part is the development of a darkbox setup for detector operation.

The pulse generator is a part of the mass test facility for functionality tests of the FlashCam readout electronics. It is planned that each readout electronics board of the FlashCam camera has to pass through this functionality test before it is installed into a FlashCam of the production phase.

The pulse generator has a *Spartan-3 FPGA Micromodule* as operating core. This FPGA controls one USB port for communication with a computer station, two trigger ports, a mechanical switch and eight output channels. Each of the eight output channels generates a sharp gradient with an individually adjustable amplitude, which is used for emulating a PDP-module-like signal with a following shaper board. The pulse generator is operated either in an internal trigger mode or in an external trigger mode. For the internal trigger mode, the FPGA generates a trigger signal that is connected to a trigger output port. A rising flank of the periodical trigger signal starts the eight individually adjustable output signals. For the external trigger mode, a trigger signal has to be connected to the trigger input port. A threshold voltage of $U_{\text{th}} \approx 0.9 \text{ V}$ starts the output signal procedure.

It could be shown that the pulse generator provides a reliable voltage difference for the sharp gradient of the output signals. A voltage measurement with the oscilloscope *Agilent infinium DSO8104A* confirmed accurate voltages. Occuring divergences are probably caused by the oscilloscope itself. The usual rise time of the sharp gradient could be estimated to be about $t_{\text{rise}} = 2.1 \text{ ns}$. The time accuracy of the internal trigger signal was

measured to be of the order of $\Delta P = 0.1$ ns.

A darkbox setup was developed to realize a miniature FlashCam consisting of three PDP modules, the appropriate readout electronics and a camera server. The design of the darkbox setup is strongly based on developments of the University of Erlangen, but with modifications especially in the opening system of the darkbox and the mounting of the optical components. It was designed to realize an opaque environment for operating optical light sensitive detectors like photomultiplier tubes. Inside the darkbox, there are a laser with 405 nm wavelength, a filter wheel controlled by a servo motor and a noptical diffuser to spatially widen the highly focused laser beam in order to homogeneously illuminate up to 36 installed PMTs. The laser can be operated either in a continuous wave mode or in a pulsed mode using an internal or external trigger mode.

A homogeneity measurement at the detector plane using the laser at high intensities showed that there are inhomogeneities at scales of about 1 mm for a distance between the detector plane and the diffuser of $d = 120$ cm. For detectors with an effective area of about $12 \text{ mm} \times 12 \text{ mm}$, this inhomogeneities are no longer present. But there is a decrease of the intensity to outer areas of the laser cone compared to its center. The scale of the inhomogeneities can be reduced by decreasing the distance between the detector plane and the diffuser taking the consequence of a smaller exposure area. On the other hand, the decrease of the intensity to outer areas can be reduced by increasing this distance.

By using one PDP module, it could be shown that there is in average a remaining trigger rate of about 5 events/s per photomultiplier tube with a trigger threshold of 10 LSB. This trigger rate seems to be caused of dark counts instead of optical photons because it could not be reduced by covering the effective area of the photomultiplier tubes.

The pulse generator as well as the darkbox setup are in an operational state. The handling of the pulse generator is optimized and the output is understood well enough for its application in the mass test facility for functionality testing of the FlashCam readout electronics. The construction goals of the darkbox with reference to the light tightness could be reached. It is now an environment for operating light sensitive detectors. Especially, operating PDP modules can contribute to a better understanding and further improvements of trigger algorithms or calibration purposes of the FlashCam camera.

Appendix A

Communication with the FPGA using the USB port

The communication with the FPGA is managed by an executable written in C++ . In the code for this program, the commands listed in Table 2.1 and Table 2.2 are defined. The object-orientated implementation comprises three files.

- **pulser.h:** The header file *pulser.h* declares the class *Pulsegenerator* with its methods. Each property of the trigger and output signal has a *set*, a *send*, a *get* and a *send status* method. With those methods the respective value is set to the virtual object and is sent to the real pulse generator. Furthermore, a value of the virtual object is requested as well as the status of sending a set value to the real pulse generator.
- **main.cpp:** The file *main.cpp* contains the method *main* and creates an instance of the class *Pulsegenerator*. This method also evaluates the input commands and calls the corresponding methods. There is also the method *print_options* which is called by typing *?* or *--help*.
- **pulser.cpp:** The file *pulser.cpp* contains the implemented methods and codes the commands and the parameters for sending them to the FPGA. Also the conversion from voltage in mV into DAC values is located here.

To use this C++ program, a Makefile is necessary to compile and link it into an ELF¹ 64-bit LSB² executable with the name *pulser_example*. This compilation is executed by typing *make* in a terminal.

¹Executable and Linkable Format

²Linux Standard Base

With the created file *pulser_example*, commands are sent to the pulse generator. For example, to adjust the plateau duration of the output signal of channel 3 to a value of 400

$$\text{sudo ./pulser_example -chpd 3 400} \quad (\text{A.1})$$

has to be written in the terminal. To change more than one parameter for one or more channels, it is useful to write a shell script. Especially if those commands will be sent several times. To avoid the sudo call, the necessary permission for the USB device is granted by an udev³ file. For a linux operating system, a text file with the content

```
SUBSYSTEM=="usb", ATTR{idVendor}=="fb9a",
ATTR{idProduct}=="fb9a", MODE:="0666", GROUP:="users"
```

has to be saved as “/etc/udev/rules.d/file-name.rules”.

In further work, a serial interface that is not depending on any specific driver or software could be implemented. For this, the premises are already present.

³userspace /dev (device)

Appendix B

Properties of the pulse generator

As mentioned in Subsection 2.1.3, the voltages of the output signal of the pulse generator (see Section 2.1) looks similar for all of the eight channels. Figure B.1 to Figure B.7 show the results of the voltage measurements for the channels 1 to 7.

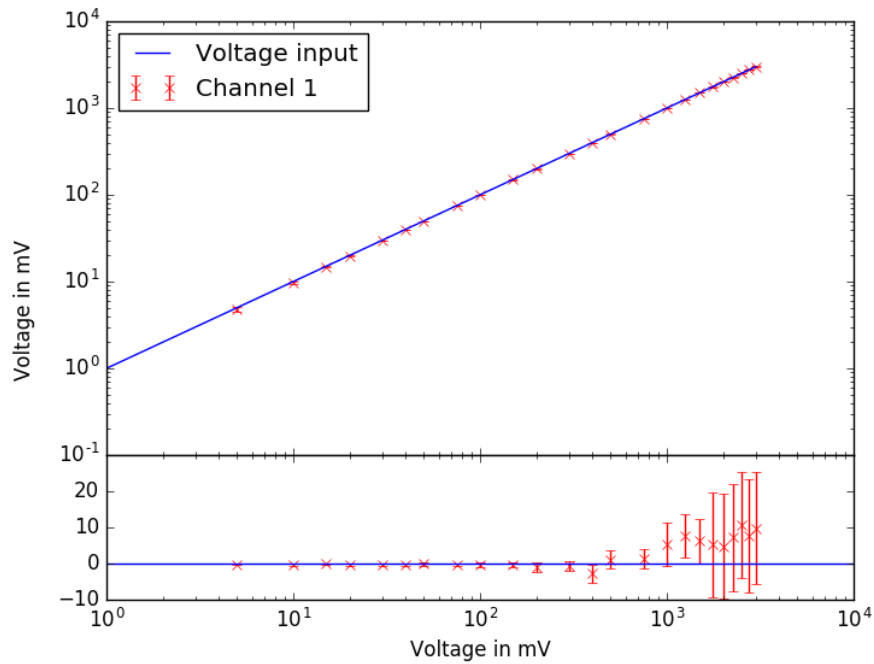


Figure B.1: Voltage measurement of the output signal of channel 1.

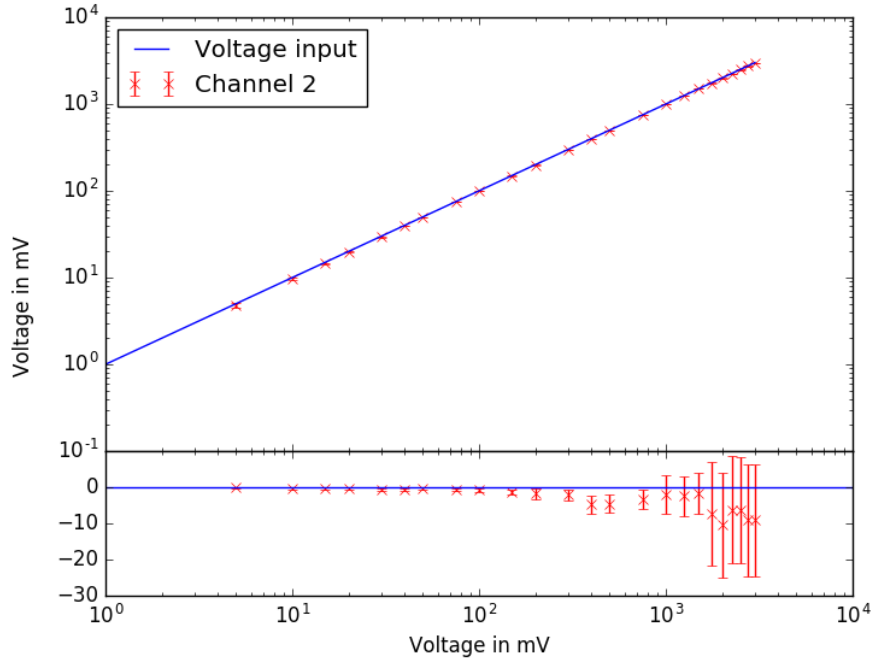


Figure B.2: Voltage measurement of the output signal of channel 2.

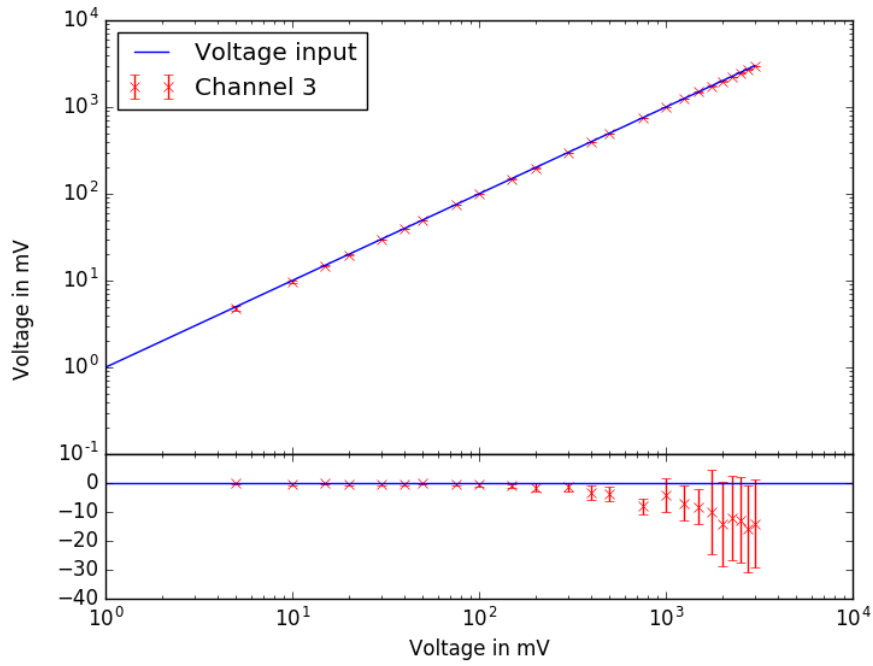


Figure B.3: Voltage measurement of the output signal of channel 3.

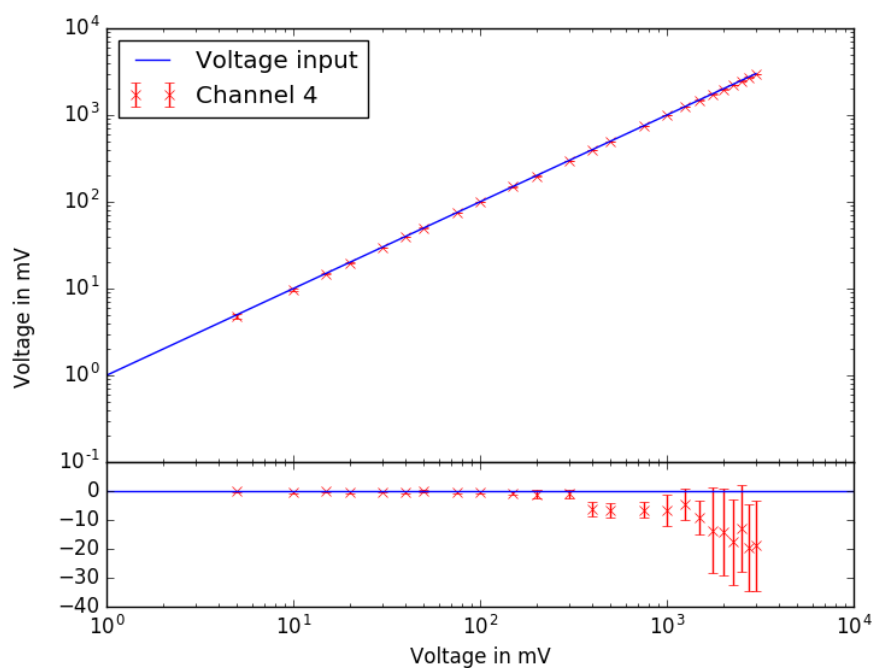


Figure B.4: Voltage measurement of the output signal of channel 4.

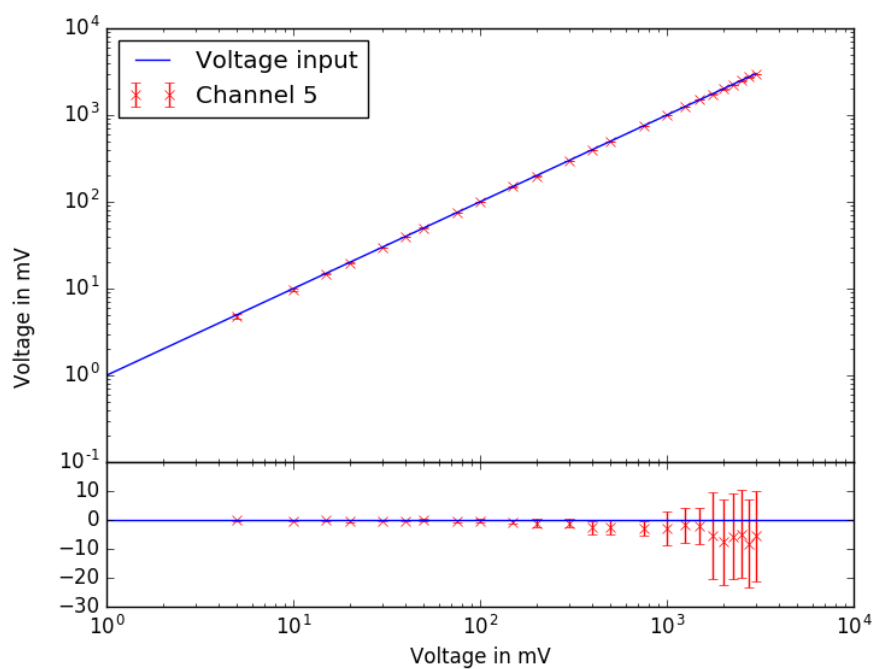


Figure B.5: Voltage measurement of the output signal of channel 5.

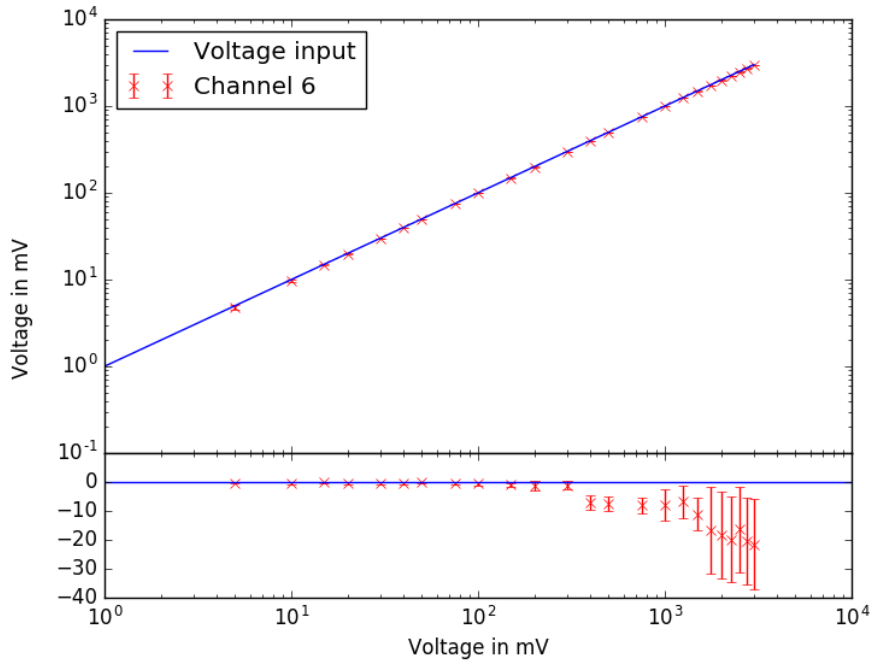


Figure B.6: Voltage measurement of the output signal of channel 6.

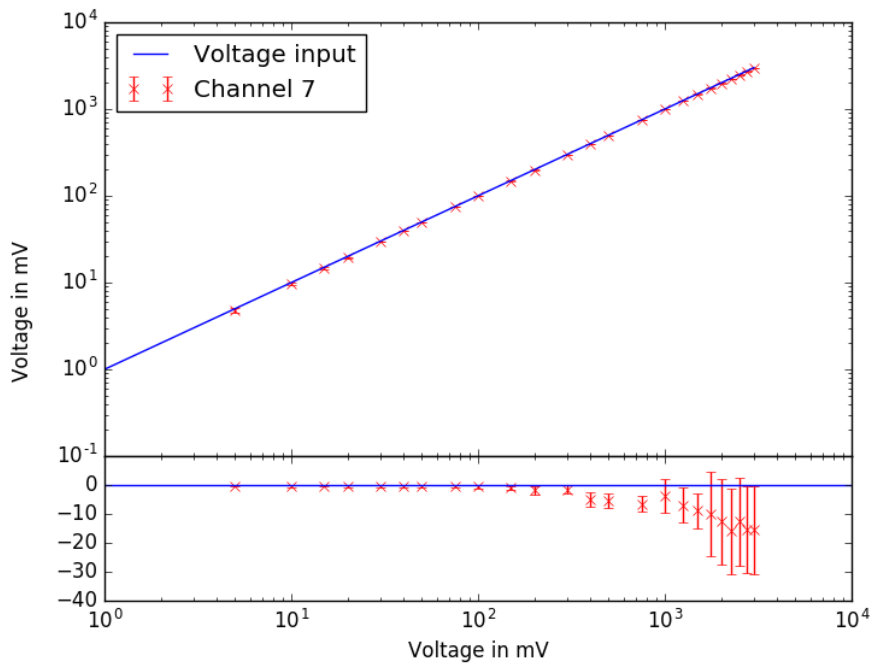


Figure B.7: Voltage measurement of the output signal of channel 7.

Appendix C

Results of an amplitude test

The results of an amplitude test with the test section presented in Chapter 2 are shown in Figure C.1 to Figure C.4. The motherboard with the number 0013 equipped with two FADC boards with the numbers 0109 and 0119 were tested for all the 24 ADC channels.

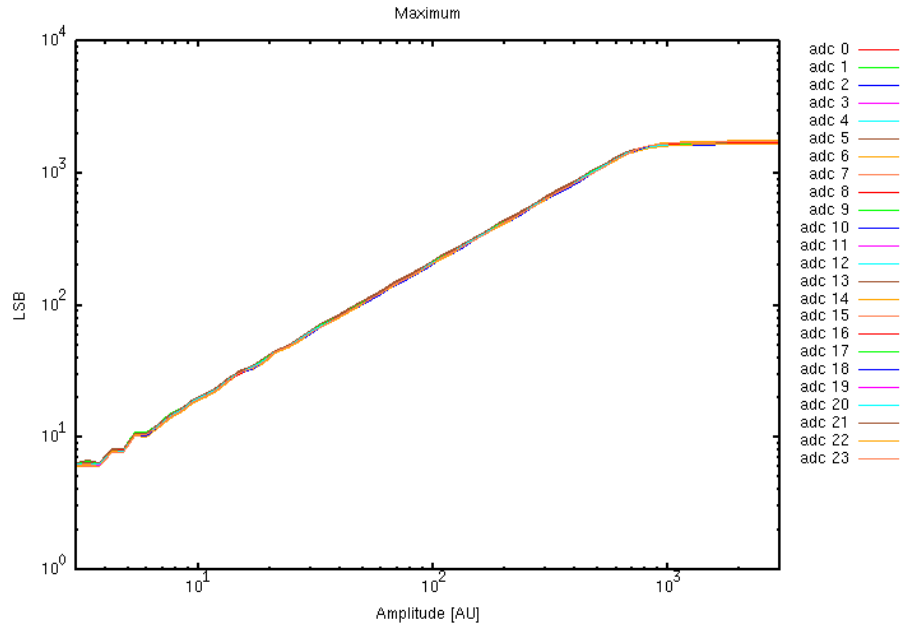


Figure C.1: The measured maximum of the incoming signal is plotted over the set amplitude of the sharp gradient of the pulse generator. The non linear regime starts at an amplitude of approximately 750 AU what is equal to a voltage of 750 V.

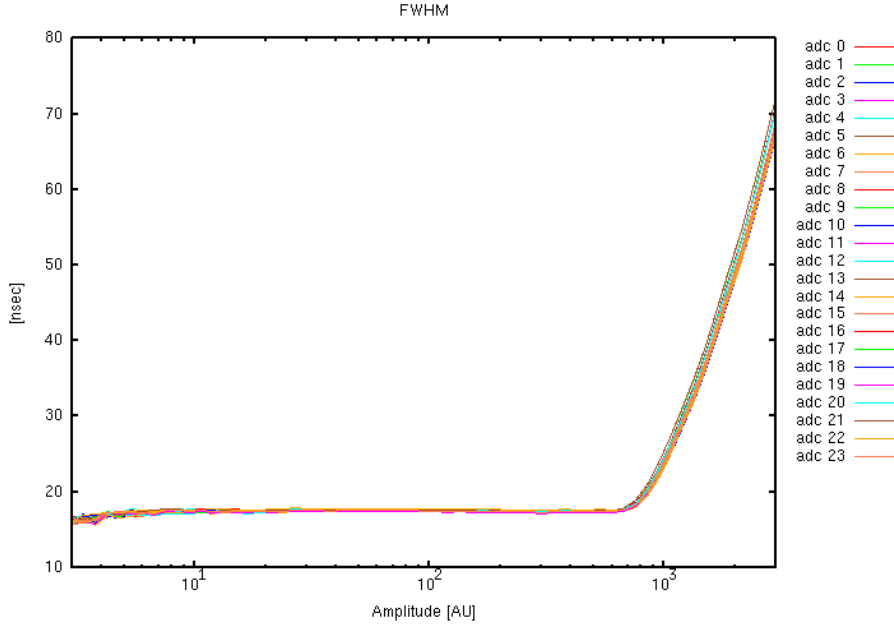


Figure C.2: The FWHM in units of time is plotted over the amplitude. For the linear regime, this property is close to be constant. With the start of the non linear regime the value of FWHM increases.

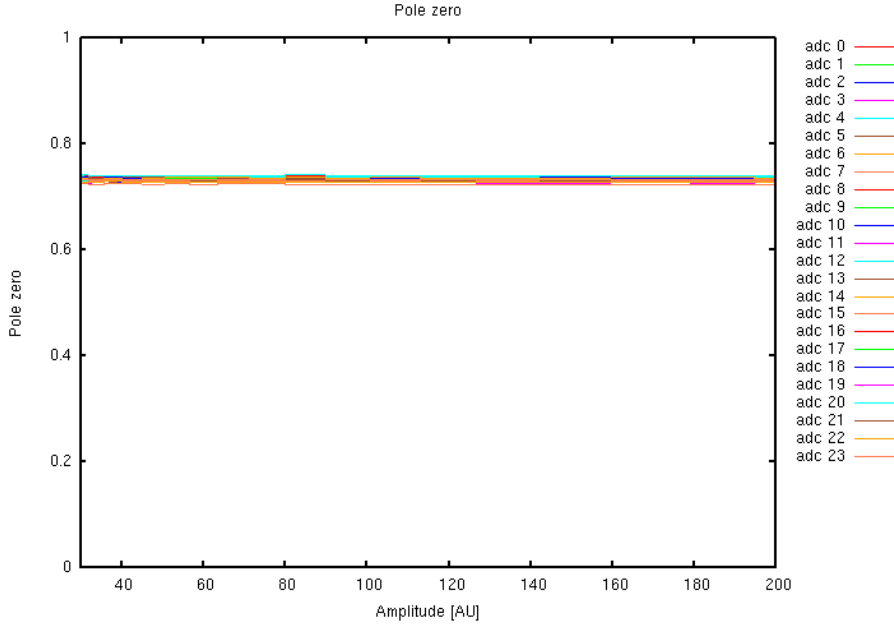


Figure C.3: The pole zero property is constant for amplitudes between 30 and 200 AU. The scale of the amplitude was limited to this interval because outside, the values for pole zero do not follow any trend.

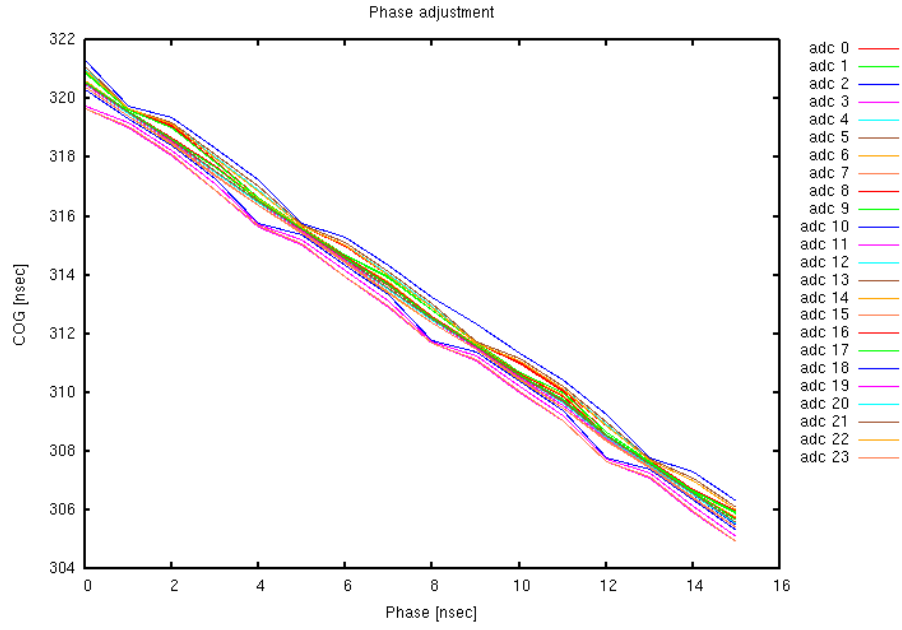


Figure C.4: The COG has a linear behavior referenced to the phase. For the COG, there is an offset of the ADC channels of up to 2 nsec.

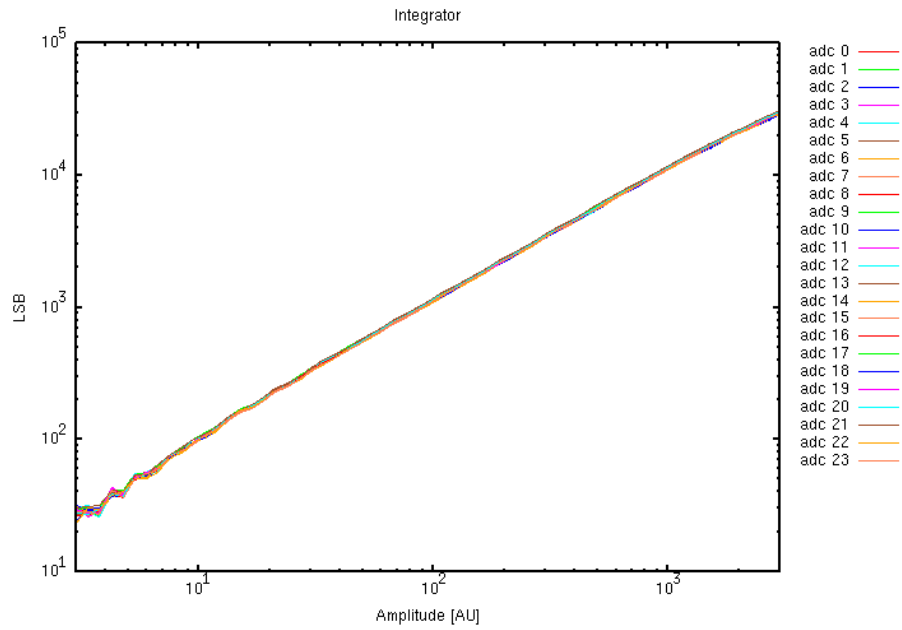


Figure C.5: The integrator shows a linear behavior over all amplitudes with a small curvature only.

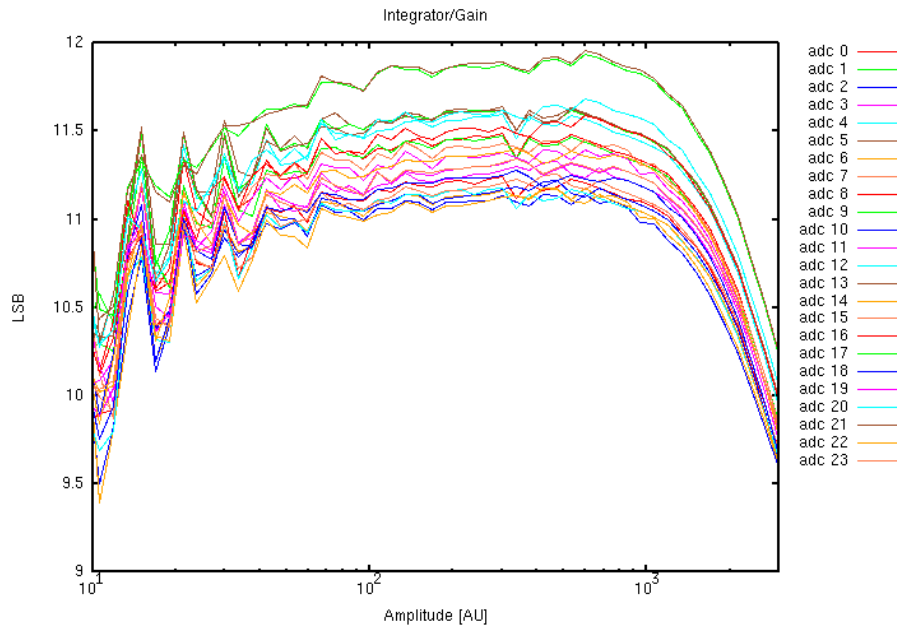


Figure C.6: The integrator/gain values have a spread of up to 1 LSB (Least Significant Bit). For amplitudes below 70 AU the plot shows an increasing trend with high scattering. Between an amplitude of 70 AU and 750 AU there is a linear interval with a negligible slope. Above 750 AU, the values of integrator/gain decreases.

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